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President of the British Association

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THE ADVANCEMENT OF Science

VOL. XVIII No. 74 NOVEMBER 1961

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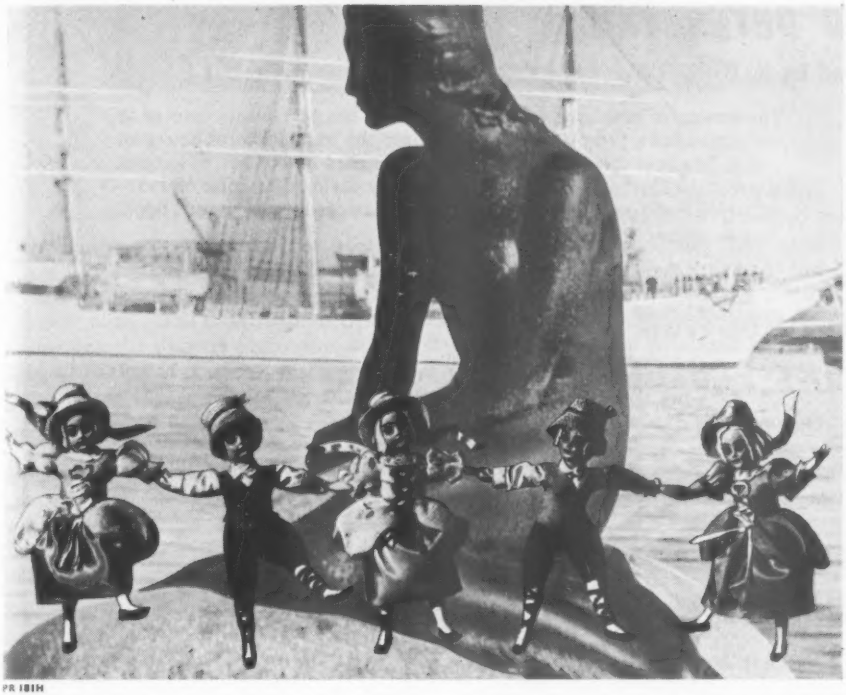

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Edited by K. DURHAM

The search for new 'synthetic' detergents over the past twenty years or so has stimulated a great deal of research into the mechanism of detergent action. Much of this recent work was summarised in a course of lectures given at the Liverpool College of Technology during the winter of 1957–58, which many people later suggested should be used as a basis for a book. This monograph is the result.

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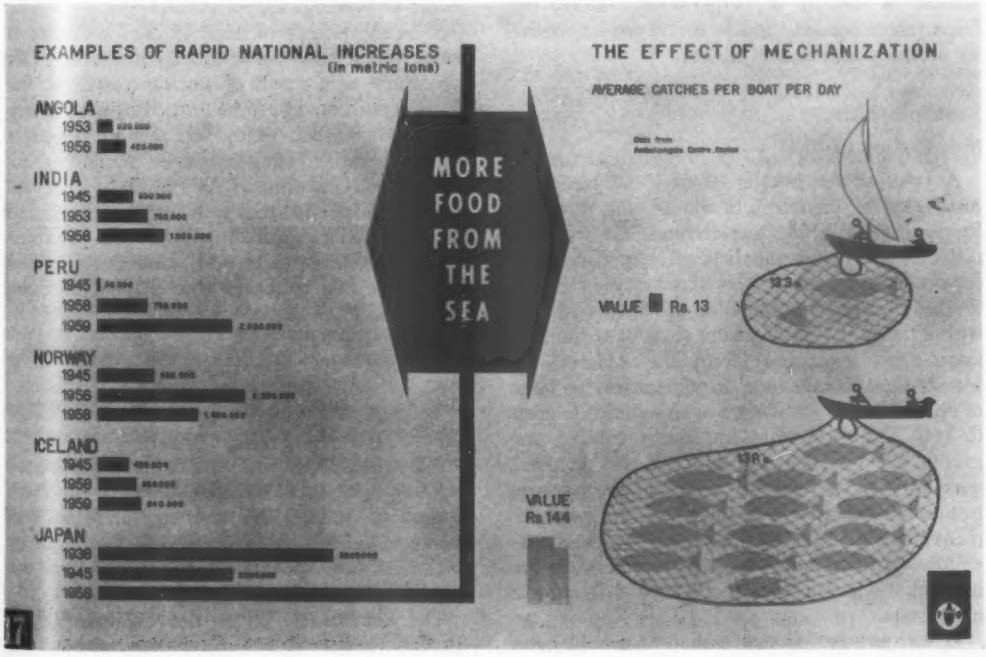
Notes and Comments

More Food from the Sea

More than 75 per cent of the earth's surface is covered by water but yields only 10 per cent of animal protein supplies and probably not more than 1 per cent of the total food supply. Experts consider, however, the primary production of the sea to be equal to that of the land. Fishing takes place only in about 10 per cent of the seas and much of it is restricted to the Continental Shelf areas. Inland waters yield about 5,000,000 tons of fish annually and these are only partially under cultivation or management. In Asia and the Far East alone there are some 40,000,000 hectares which could be more extensively cultivated.

World fish production has increased from about 20,000,000 tons to around 35,000,000 tons annually over the last ten years. An even more rapid increase could be attained if more improved fishing gear and mechanisation could be introduced in many of the less developed countries. Ceylon provides a striking example. There, 60,000 people live mainly on fishing, but have only been catching some 30,000 tons of fish per year—about 20 lb. per week per fisherman. In 1951 there was not a single motor-powered fishing boat in operation, except for one steam trawler. F.A.O. sent a master fisherman, and, later, a marine engineer, to Ceylon to advise on mechanisation. Some 300 boats have



now been mechanised, and government plans call for building 300 more each year—small inshore craft, trawlers and tuna boats.

The difference in the catches of the traditional boats and the mechanised boats is striking. At one of the F.A.O. centres, the traditional sailing boat catches 13·3 lb. of fish per day worth 13 rupees, whereas the same boat equipped with an outboard motor catches 139 lb. per day worth 144 rupees. Fish caught by the mechanised boat fetches higher prices because it arrives earlier at the market and is fresher.

F.A.O.

Sugar Will Kill Eelworms

Ordinary sugar mixed into soil will kill nematodes, microscopic eelworms which are considered to be among the world's most destructive pests, U.S. Department of Agriculture researchers have found. The Department says sugar is the first known nematode-killing material discovered which does not hurt warm-blooded animals and which leaves no residue in the soil. Soil treatment by this method is still in the experimental stage, the Department reports, and is much too expensive for ordinary farm use at present.

Science Horizons

New Carbon Isotope

A new carbon isotope of mass 16 has been discovered by physicists of the Atomic Weapons Research Establishment, Aldermaston, working in collaboration with scientists of the Clarendon Laboratory, Oxford.

These scientists bombarded a carbon-14 target with a beam of 6 MeV tritons (ions of tritium, or super-heavy hydrogen) from the Aldermaston Van de Graaff accelerator. In some cases, the force of the collision was observed to be sufficiently great to split the triton into its constituents of one proton and two neutrons and the two neutrons were captured by the carbon-14 to form a new isotope carbon-16. By making precise measurements with a large magnetic spectrograph on the emitted protons they were able to determine the mass of the new isotope to be 16·014702 atomic mass units.

It was anticipated that carbon-16 would beta-decay like carbon-14 and carbon-15 but with the difference that the product of the decay would still have sufficient energy to emit a neutron. This was observed to occur and use was made of this property to measure the half-life. The measurements showed that carbon-16 has a half-life of only 0·74 seconds which is even shorter than that of carbon-15.

Naturally occurring carbon consists of two isotopes, i.e. it contains two kinds of atoms chemically indistinguishable but having slightly different masses. The most abundant isotope is carbon-12 which has a mass of 12 units but also present is 1·1 per cent of an isotope of mass 13. The nuclei of both isotopes contain 6 protons and differ by having respectively 6 and 7 neutrons which results in their difference in total mass.

A third isotope of carbon, of mass 14, does occur in nature but in a rather unusual way. This is created in the atmosphere by the bombarding action of cosmic-ray particles. It is, however, radioactive and decays by emitting beta-particles, with a half-life of about 5600 years. This isotope forms the basis of the carbon-14 method of dating archaeological specimens.

A carbon isotope of mass 15 does not occur in nature but it has been artificially produced in the laboratory as a result of nuclear reactions. For example, carbon-15 can be formed by bombarding a target of carbon-14 by fast moving deuterons (the nucleus of heavy hydrogen containing one neutron and one proton). As a result of a collision a deuteron is sometimes split into its constituents and a neutron is captured by the carbon-14 to form carbon-15. Like carbon-14, carbon-15 is also radioactive and it decays with a relatively short half-life of 2·25 seconds.

Atom

The Royal Society and Scientific Research in Schools

A Committee on Scientific Research in Schools was first established by the Council of the Royal Society in March 1957 and the following brief report will give some indication of its activities up to the end of October 1960, a period of some two and half years.

The Committee, under the Chairmanship of Sir Lindor Brown, has met either three or four

times a year and for the last year has consisted of Dr. F. P. Bowden, Sir Edward Salisbury and Dr. C. G. Williams for the Royal Society and Messrs. W. Ashhurst, R. H. Dyball and J. L. Lewis for the Science Masters' Association. Since October 1960, however, Dr. F. P. Bowden has taken over the Chairmanship and Dame Kathleen Lonsdale has become a member of the Committee.

An increasing number of schools have become interested and have undertaken research and the Committee is now administering research projects in 57 schools. Several of these schools, indeed, have more than one research project under way and a total of 68 separate projects are now being actively pursued compared with 57 in 1959.

During the year ending October 31, 1960, a sum of £2000 has been provided by the Council of the Royal Society, and Shell Research Limited have generously given an additional £75 for special assistance at one school.

All the research projects with which the Committee is dealing are carried out with the special advice and assistance of Fellows of the Society and by others who have most generously agreed to act as advisers. This generous response has been much appreciated by those carrying out the research and has been of the utmost assistance to the Committee in its work.

The Committee will assist any schoolmaster or schoolmistress who seeks advice and makes known their desire to undertake a scientific research project; the Committee does not suggest research problems but leaves it to the master or mistress concerned to make their own proposals. The general procedure then is to ask a Fellow of the Society who lives in the vicinity, and who is an authority on the proposed subject, to meet the proposer and discuss the research project and to report whether the project is a suitable one and that there is a reasonable certainty that the proposer will be able to carry it out. Advice will also be given concerning apparatus and books required, and if the proposer does not possess any of these items the Committee is prepared to make a grant towards their purchase.

The person undertaking the research is asked to keep in touch with his adviser and to report to the Committee once a year giving news of the progress of the research. Furthermore the Committee enjoin that the research shall be carried in the school laboratories or in the vicinity of the school itself, thus ensuring that some of the senior pupils may share in its interest and be inspired by its possibilities.

The quality of the research has in general reached a high standard and it appears likely that in the near future a number of scientific papers will be prepared by those schoolmasters whose projects have reached a state where publication is possible and desirable. These papers will be prepared in consultation with the advisers and will be published by the appropriate scientific societies.

The following two schoolmasters have already published papers:

W. H. Dowdeswell (Winchester College) on 'Further studies on micro evolution in the butterfly *Maniola jurtina* in the Isles of Scilly', *Heredity*, May 1960.

A. G. Long (Berwickshire High School), 'On the structure of *Calymmatotheca kidstoni* Calder (emended) and *Genomosperma latens* gen. et sp. nov. from the Calciferous Sandstone Series of Berwickshire', *Transactions of the Royal Society of Edinburgh*, May 1960.

Schools at which research projects are being carried out include the following:

The Academy, Kilmarnock	Studies on life-cycles, growth and fecundity in population of land isopods.
Alcester Grammar School, Warwickshire	Soil aeration in relation to other factors.
Aldridge Grammar School, Staffs.	Research in histology.
Berwickshire High School, Duns.	Research on fossil plants.
Bletchley Grammar School, Bucks.	Reactions of amine hydrochlorides with sodium borohydride.
Bolton School, Lancs.	Reinvestigation of the reactions of some dihalodiphenyls with metals and metallating agents.
Bradford Grammar School, Yorks.	The Zeeman effect.
Brentwood School, Essex	Work in the field of ferro-magnetism.
Bromsgrove School, Worcs.	Solution properties of styrene and cinnamic acid.
Canford School, Wimborne, Dorset	Nitration and nitrosation by tetranitromethane.

City College of Technology, Liverpool	Selective uptake of bactericides and bacteriostatics by micro-organisms.
The College, Llandovery	Survey of certain invertebrate groups in three local rivers.
Collyer's School, Horsham	Corrosion of lead.
Coleshill Grammar School, Warwickshire	Ectoparasites on birds and animals.
Colne Valley High School, Nr. Huddersfield, Yorks.	Research on the effect of growth substances in water uptake in plant tissues.
County High School for Boys, Ilford, Essex	Research on freshwater algae.
County Secondary School, Llangefni	Kinetics of the acetolysis of some sugar halides.
County Secondary School, Tregaron, Cardiganshire	Elastic constants of crystalline materials.
Denstone College, Uttoxeter, Staffs.	The age of fossils and rocks by analysis of their pollen distribution.
Derby School	Ionic equilibria.
Dover College, Kent	A quantitative petrological analysis of the Blackheath Pebble beds.
Eltham College, London	Maturation of gonads in the cockroach *Blaberus discoides*.
The Grammar School for Boys, St. Albans, Herts.	Ecology of Phytoplankton.
	Metal corrosion.
The Grammar School, Heywood, Lancs.	Preparation of fluoronaphthyl hydrazines.
Hackney Downs School, London	Feeding mechanism of Marine isopod Sphaeroma.
Handsworth New Road Boys' School, Birmingham	The laboratory culture of liquicolous fungi and the leucoanthocyanin micro-organisms.
Hanley High School, Bucknall, Stoke -on-Trent	Effect of certain chemicals on the germination of seeds.
Hillfoot Hey High School, Woolton, Liverpool	The orientation of indanthren Brilliant Scarlet R.K.
Ifield Grammar School, Crawley, Sussex	Taxonomic research on insects (genus *Cariothorax*, Coleoptera).
Ipswich School, Suffolk	'Whistler' atmospherics.
King's School, Bruton, Somerset	Study of O and P-Hydroxy carbonial compounds.
	Study of the pineal body of the Lamprey.
Lady Lumley's Grammar School, Pickering, Yorks.	The heterocyclic compounds of sulphur.
Malvern College, Worcestershire	Research into the teaching of nuclear physics.
	Study of minerals in the Pre-Cambrian rocks of Malvern.
Marlborough College, Wilts.	Kinetics and mechanism of some enzyme catalysed hydrolysis reactions.
	Magnetic properties of paramagnetic materials.
	Redox titration of organic compounds.
	Research on the nervous system of annelids.
Merchant Taylors' School, Northwood, Middlesex	Action of acids on metals and the quantitative determination of metal ions in solution.
Mount St. Mary's College, Sheffield	Diazotisation problems.
Oldbury Grammar School, Langley, Birmingham	Selective breeding of *Drosophila melanogaster*.
Portsoy School, Banffshire	Research on methods of utilising solar radiation.
Poundswick Grammar School, Manchester	Diatom-analysis of the sediments of a tarn of the Lake District.
Radley College, Abingdon, Berks.	Chemistry of chlorine dioxide with reference to its action on organic chemicals.
Repton School, Derby	Time and space distribution of aquatic fauna of the Old Trent.
	Preparation of a long-pollen diagram of post-glacial lacustrine deposits near Swarkestone, Derbyshire.
Rutherford Grammar School for Boys, Northumberland	Fossil deposits.
St. John's School, Leatherhead	Research on radio-active isotopes.
St. Modan's High School, Stirling	Synthesis of the dibenzofluoranthene series.
Southgate County Grammar School, London	Seasonal variation in reproductive system of reptiles.
Stanborough School, Watford	Research on Vitamin B_{12} in foods and diet.
Stretford Grammar School	Reactions of diazomethane with aromatic hydroxy aldehydes.

Tividale School, Tipton, Staffs.	Metabolic products of nitrogen-fixing soil organisms.
Tonbridge School, Kent	Expansibility of plastics.
Uppingham School, Rutland	Solubility of common gases in pure hydrocarbons.
Warwick School, Warwick	Internal parasites of caddis Larvae.
Wellington College, Berks.	Inhibition of hydrocarbon oxidation by amines.
Westminster School, London	Radio Astronomy.
Whitgift School, South Croydon	Organo-metallic peroxides.
Winchester College, Hants.	Investigation by physical methods of ions and anions in aqueous solutions.
	Investigation of the moss *Amblystegium serpens*.
Wycliffe College, Stonehouse	Mode of action of soil insecticides on wireworms.
Ysgol y Preseli, Pembrokeshire	Thermodynamics of non-electrolytic solutions.

The Committee on Scientific Research has been much stimulated by this continued and growing response to the scheme and looks forward both to receiving further requests from schoolmasters and schoolmistresses, and to the continued support of the Fellows of the Royal Society and others in acting as advisers and assistants in the extension of its activities.

Mediterranean Project

From the dawn of human history, until the industrial revolution began in England some 150 years ago, the Mediterranean basin was the undisputed centre of Western civilisation. Yet today, with populations rising and the productivity of the land declining, the countries in this area are blighted with want. About 170 million Mediterranean people—a population comparable to that of the United States—must share a total gross output about a tenth of the value of that of the United States.

Decline of Natural Resources

Mismanagement of the soil has been a feature of the region for centuries, largely resulting from efforts to increase production to meet rising demand. Such a robber economy that destroys forests and wastes soil, has held sway in almost every part of the world. But, unfortunately, the environment of the Mediterranean is less tolerant of abuse than temperate areas. Forests and good grazing lands on mountains and hills have shrunk to one-fourth of what they were in ancient times and the remaining acreage is either covered with degraded vegetation, or consists of bare rocks, denuded hillsides and deep gulleys. The poor and underfed livestock produce only a fraction of the milk and meat that they should.

When F.A.O. first considered the possibilities of launching a Mediterranean Development Project, the most obvious prescription for the problem appeared to be 'Turn the clock back and restore the past' or, alternatively, 'Import the industrial revolution and move into the twentieth century'.

The first idea required a vast reforestation programme but, unfortunately, the extent of the destruction of the soil has made it impossible to restore the ancient forests within, say, a decade or so.

The second notion of 'overnight industrialisation' has been tried during the last 15 years, with the help of substantial foreign aid, in almost all Mediterranean countries. Between 1945 and 1953, the national income in most of these countries rose significantly. Since then, however, progress has slowed down, come to a standstill in certain cases, and the beginning of a self-sustained growth has not occurred.

Balanced Use of Land

F.A.O. advocates a third solution—the simultaneous development of agriculture and forestry tied into an integrated plan for general economic development. To do this, it is essential to relieve the pressure of over-grazing and to restore the forest cover and other vegetation wherever this is possible and appropriate. To this end it will be necessary to remove shepherds and their flocks from forest and eroded range lands to reduce the area cultivated and, perhaps, even the size of herds.

The key to all this is water. The long dry season, the excessive concentration of torrential rainfall in winter and the salinity of poorly drained soils have been throughout history, and remain to this day, the main physical factor limiting Mediterranean

agriculture production. Investigations already made by F.A.O. show that it should be possible to increase the irrigated area by 25 million acres between now and 1980, bringing the total to 45 million acres or 70 per cent of its potential. The total cost of the irrigation programmes recommended by the Mediterannean Development Project would amount to 7·3 billion dollars.

Increasing Productive Capacity

Irrigation would make it possible to grow more than one crop per year on the same land. So called 'double cropping', with vegetables and fodder grain in rotation with crops such as cereals and cotton, becomes feasible. But the principal cash crop on the newly irrigated land will be fruit and high quality vegetables. It is expected that the production of citrus fruits, for example, will rise from the present one million metric tons to some 3·2 million tons by 1980.

New practices and techniques will also bring considerable changes to the two million acres that are now cultivated under dry farming. This objective calls for nothing less than a complete modernisation of Mediterranean agriculture, specifically in the massive use of fertiliser and mechanisation and in the introduction of better seed.

Seed, fertiliser and farm implements are largely imported commodities. F.A.O. plans to help the Mediterranean countries establish industries to produce these.

At the very foundation of all these plans for agriculture and animal husbandry lies the programme for the restoration of the forests of the Mediterranean area. F.A.O. proposes that the governments plant some 18 million acres of forest during the next 20 years and restore another 25 million acres of forest, principally in Spain, Turkey, Greece and Algeria.

The improvements that could be achieved by 1980 have already been forecast, but at this stage it is not possible to foresee the practical results. That depends on the governments of the countries in the region. F.A.O. thinks, however, that the Mediterranean region could achieve by 1980 an increase of $60 billion per year in the gross output of the region as a whole and the doubling—by and large—of *per capita* income per year.

Obstacles to Overcome

There are three main stumbling blocks to such development: the unbalanced system of land tenure, the excessive fragmentation of farm holdings, and the primitive structure of rural society.

The transformation of the family and community spirit into co-operative spirit is the most promising way to modernise these rural societies without an abrupt departure from old traditions. F.A.O. contemplates setting up a network of community development experiments, linked to the pilot zones in which the new technologies and patterns of land use are to be demonstrated.

The financial problem is also very difficult and substantial foreign aid will be required to achieve the goal, some of which may come from contributions raised by F.A.O.'s Freedom from Hunger Campaign. It is one of the critical challenges of our time, however, to create a partnership between rich and poor countries which will enable the latter to achieve substantial growth within the political framework of democratic development. The blueprint for economic action in the Mediterranean which F.A.O. has provided shows how this partnership can be made effective in one important region of the world.

F.A.O.

ANCIENT FIELDS

The B.A.'s research committee on Ancient Fields has now published a booklet on ancient field remains which may be obtained from the Secretary of the Association at a price of 7*s*. 6*d*. plus postage 9*d*. The booklet considers the nature of agricultural earthworks; it would be presumptuous to call it a 'grammar' but that would describe its approach. It considers basic farming practices, attempts to analyse the nature of field remains and offers some suggestions on the typology of 'Celtic' fields, 'strip lynchets', and ridge-and-furrow. It also discusses methods of work. It has an annotated, selective bibliography and an appendix which lists leading subjects for research.

There is a real need for a large number of people to become seriously interested in these field remains and the Committee hope that the booklet will provide a useful background for detailed

investigations. Some modification of its tentative generalisations may, as a result, be found to be necessary, but if due to new fieldwork the booklet will have served its purpose.

Although the title of the booklet is 'Ancient Fields' it may be remarked that some of the remains discussed are relatively modern and many earthworks are briefly considered which are not fields. The reason is that fields are only one aspect, however predominant, of farms, and the remains of the 'farms' have to be searched out from continuously developing countryside. It is hoped, indeed, that the booklet will be of some interest and use to all who are concerned with what man has done to alter the shape of his environment.

H. C. BOWEN

HUNGER—CAN IT BE AVERTED?

Hunger—Can it be Averted?, published by the British Association for the Advancement of Science.

This book presents the views of a small group of distinguished scientists invited by the British Association to discuss the part that science can play in relieving the hunger prevalent in some of the under-developed countries, and in averting the catastrophic suffering inevitable if world population should outstrip man's power of producing food. As Sir John Russell, O.B.E., F.R.S., says in his preface to the book, 'their broad conclusion is that hunger need not be feared for at least the next forty years *provided that existing scientific knowledge can be properly applied.*'

An introductory chapter by Dr. Norman C. Wright, C.B., Deputy Director-General of F.A.O., on 'The current food supply situation and present trends', is followed by an essay on 'Population prospects and their implications' by Prof. D. V. Glass, Professor of Sociology in the University of London. Prof. W. A. Lewis, Principal, University College of the West Indies, then considers 'Economic conditions for greater output', and Prof. L. Dudley Stamp, C.B.E., Director, World Land-Use Survey, problems of 'Land use and food production'. The two remaining chapters are contributed by Lord Fleck, K.B.E., F.R.S., a Past President of the Association, on 'Industrial and technological needs', and Prof. H. D. Kay, C.B.E., F.R.S., Emeritus Professor of Biochemistry in the University of Reading, on 'What limits food production?' Prof. P. M. S. Blackett, F.R.S., Professor of Physics at the Imperial College of Science and Technology, reviews the problem as a whole in a final chapter entitled 'Some conclusions'.

Copies of *Hunger—Can it be Averted?*, which has been edited jointly by Dr. N. C. Wright, C.B., O.B.E. and Sir E. John Russell, F.R.S., and is fully illustrated, may be obtained from the Secretary of the British Association, No. 3, Sanctuary Buildings, Great Smith Street, London, S.W.1 (or ordered through any bookseller) at a price of five shillings, post free.

TECHNOLOGY AND GEOGRAPHY*

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Since I attended my first British Association meeting in 1931, twenty-four Presidential Addresses have been given to Section E (Geography). Their titles range from the vast global sweep of 'The Human Habitat' by Sir Halford Mackinder in 1931 and appraisals of the nature and content of our subject ('Geography as Mental Equipment' —Lord Meston, 1933; 'Geography as a Social Science'—Lord Rennell, 1948; 'The Geographer as Humanist'—Kinvig, 1953) to reviews of different aspects of physical geography ('The Upland Plains of Britain'—Wooldridge, 1950; 'The Everlasting Hills'—Linton, 1957) or of human geography ('The Changing distribution of Population'—Fawcett, 1937; 'The Atlantic Ends of Europe'—Evans, 1958). I cannot discover a single one which was frankly economic in its approach, though several, such as Stamp's 'Planning of Land Use' (1949) and Buchanan's 'Settlement in Overseas Dominions' (1952) inevitably had an economic slant. And I do not think the word 'technology' has entered into any of them. I make no apology, therefore, for developing what seems to be a somewhat neglected facet.

May I begin by using an old trilogy in a new form. For well over half a century W. M. Davis's 'structure, process, stage' has been the basis of much of our work in physical geography, but so far as I know no one has attempted to interpret the man-made landscape in similar terminology. Without pressing the analogy too far, I suggest something like the following train of thought:

(i) *Structure.* This, in human geography, is the nature of the population, its ethnic characters in particular, and the energy and initiative of its members, especially in relation to the climatic environment.

(ii) *Process.* This is the process of land occupation, the methods by which the land has been occupied, and its resources developed, during the period of human history. This clearly follows a broadly evolutionary pattern, in that primitive techniques are followed by more advanced and complex techniques of utilising the land and its resources, so that a sequence of occupational forms can usually be traced. The third element, therefore

(iii) *Stage*, is the stage which the occupationary processes have reached. There are 'youthful' human landscapes, as in the 'pioneer fringe' zones of the world, there are 'mature' landscapes where great changes are still in progress after only a century or two of human occupance—as in parts of the United States for example—and there are 'senile' landscapes, like many of those in Britain and Europe and the Far East, which represent the results of several thousand years of human occupation.

Just as in Davis's erosion cycle, so it is seldom that the evolution of the human landscape proceeds smoothly for very long. Interruptions and distortions are frequently discernible. The 'rejuvenations' of the geomorphologist are represented in the human cycle by an influx of new people (like the Romans in Britain or the whites in East Africa), by the development of new cultures, and above all by the changing techniques of human occupance, now slow and gradual, now revolutionary in character. And just as a rise in the base-level of erosion brings the evolutionary process to a halt and in a sense reverses it, with deposition taking the place of erosion, so occasionally the evolutionary lines of human progress will come to a dead-end, as the development of North Africa did after

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the fall of the Roman Empire, for example. The result, as with the physical landscape, is the production of a polycyclic human landscape, often of great age and immense complexity, which invites all the resources of the geographer for its analysis and explanation.

It would clearly be possible to elaborate this theme so as to occupy the whole of this address. But I wish to take up one part of it only—the 'changing techniques' to which I have just referred. All human activity takes place in an environment which has three major aspects, physical, technical and economic. Each of these is subject to change—though the first is the most stable—and each will vary in its importance according to the nature of the activity.

The physical environment comprises the underlying geology and the soil cover, the surface configuration of the land, and the climate. In the case of agriculture, all these will be of importance. For extractive industry the geology will be vital; for modern light manufacturing industry the whole of the physical environment may have but little significance.

The physical environment itself is virtually immutable by man, though for hundreds of years the Dutch have been reclaiming land from the sea, and even a century ago it was possible to sever the land connection between Asia and Africa by the cutting of the Suez Canal; whilst with modern engineering techniques it is possible, if not to remove mountains, at any rate to divert water through their watersheds and to carve up the land surface with very striking effect.

The economic environment is of immense importance in almost all human activity; very few parts of the world are completely without money or other tokens of exchange. They say in the north of England that 'no one does owt for nowt'; even leisure has to be paid for, and all productive activity must be related to costs of production (including interest on borrowed capital, costs of raw materials, fuel and power, transport, labour), selling prices, tariffs and taxes. Here clearly is an ever-changing environment, and one capable of much manipulation by man.

Another aspect of the economic environment is concerned with the social habits and customs of the people, which influence the kind of consumer goods which they need or the type of agriculture which they practise. I need do no more than instance the very remarkable change in the spending habits of the British working classes during the last few decades. The formerly 'middle-class' habit of spending money in improving the amenities of the home, running a car, etc., have spread down the social scale with results that are obvious to all in the vast growth of the motor car industry and of the manufacture of washing machines, television sets and other means of 'keeping up with the Joneses'.

The technical environment comprises the technical aids which are available to assist the 'process' of land occupation and resource development. Here is an environment of great complexity, from the primitive digging-stick and water wheel to the blast-furnace, the chemical insecticide and atomic energy; an environment which varies immensely from time to time and from place to place.

The interest which the technical environment has for the geographer is largely concerned with the changes in geographical values which are brought about by inventions and innovations, or to put it more simply, by changes and improvements in ways of doing things. Within the total geographical environment all the many components have their respective values in relation to any particular activity at any given time. Alter one of the components and the relative values of the others will change.

I propose first to examine the mineral industries in the light of this conception of the three-fold environment.

The *physical environment* is here of exceptional importance, since mines and quarries can only be opened where the long and complex geological evolution of the country has resulted in the presence of mineral wealth. The location of our mineral deposits is unalterable, and in this sense the physical environment is completely stable. But there are two factors which affect this stability. First, that our knowledge of the mineral resources of this country, though it has been accumulating over a long period of time, is still not necessarily complete. Most of our metallic ores were known to the Romans—particularly lead, copper and tin, and some of the iron ores—but it was still possible, in the mid-nineteenth century, to discover, or rediscover, the Jurassic ironstones, and in the

twentieth century we have witnessed the search for oil, successful in Nottinghamshire, unsuccessful in most other localities, and the incidental discovery in north Yorkshire of potash. Secondly, all minerals are won by what is commonly termed a 'robber economy'; they are wasting assets, and once the deposits have been worked out there is no means of encouraging any more to grow in their place. It must eventually happen, then, not only that individual mines and quarries come to an end through the exhaustion of their deposits, but also that whole mineral fields must ultimately be worked out. Thus coal mining in the Black Country is virtually extinct, and the Forest of Dean field has but a few years' lease of life: the great Cleveland iron ore field, which gave rise to Middlesbrough and was once our most important source of ironstone, is now but a shadow of its former self and is within measurable distance of exhaustion.

Apart from actual location, three other aspects of the physical environment have an important bearing on the working of minerals. In the first place there is the geological mode of occurrence of the ores or rocks, i.e. their stratification, if any, their thickness, the depth at which they occur and the tectonic disturbances—folds and faults—which may have influenced their dip or their underground behaviour. These features are clearly unalterable, and they severely limit, if they do not actually control, the technique of extraction.

Secondly there is the quality of the minerals; for example the metal content of ores, and their chemical composition (which may control the method of their utilisation), and the chemical nature, texture and other physical properties—such as hardness, porosity, crushing strength, refractoriness, etc.—of rocks. This quality factor is intimately bound up with the technological factors to which I shall refer in a moment. In many cases it is the most important of all in deciding just exactly where minerals shall be worked, and a few examples may be cited.

The metal content of the Jurassic ironstones fluctuates between about 23 and 33 per cent; when the figure drops below 23 the ore is generally considered to be not worth working—though the actual lower limit of workability depends also on the relative proportions of lime and silica in the ore.[1] Although the geological outcrop of the Marlstone formation, then, or of the Northampton Sands, is virtually continuous for perhaps tens or scores of miles through the East Midlands, the actual workable orefields are much more restricted. This is a relatively familiar example. It is less commonly realised that the economically workable resources of such minerals as clay, chalk and limestone, sand and gravel, are also severely limited by considerations of quality—though it is true that other circumstances, such as transport facilities and relation to markets, also enter the picture. To the uninitiated it may well seem ironical that with hundreds of square miles of country shown on the geological map as 'Chalk' or as 'Carboniferous Limestone', the industrialists should so frequently appear to have deliberately selected the most conspicuous sites, or the areas of finest scenery, for their operations. But chalk and limestone have a varying content of carbonate of lime, and this affects lime-burning and whiting manufacture, and also the cement industry. In some limestones, too, magnesia is an important constituent, and this is of significance in the use of the stone for flux and for refractory purposes. Even gravel is of many different qualities and a very large proportion of what the geologist maps as 'sand and gravel' is in fact quite worthless from a commercial viewpoint; much of the glacial and 'plateau' gravel is too irregular and dirty to yield the high quality aggregates which the civil and structural engineers now require, and a premium is placed on the low-lying river terrace gravels.[2]

A third aspect, of particular importance in the case of quarried minerals, is the surface configuration of the land beneath which they lie. This is the least immutable of the physical factors, for clearly every quarry alters it. But the original surface exercises a considerable influence on the form of the quarrying operations and on the relation which the quarry will bear to the landscape. Thus quarries in a flat surface will excavate downwards and form a hole, whilst quarries excavated into hillsides may advance horizontally; naturally the latter will be much more conspicuous than the former.

The *technical environment* has two aspects: first, the techniques of production which are available to the mineral industry, and secondly the techniques which are available for the utilisation of the mineral products. Here is clearly a constantly changing field, intimately related, too, to the

economic environment, since advancing technology so often means either the cheapening of production or increased output or both. Increasing mechanisation has been the dominant note in the production of both mined and quarried minerals during the last few decades, but particularly since World War II. In coal mining the advances in mechanical cutting and loading and in underground haulage have been considerable, and the new and reconstructed pits working on the horizon-mining principle are producing entirely new features of the industrial landscape, with their concrete-encased pit-head gear and general absence of spoil-heaps. In the quarrying industries the advent, largely within the last thirty or forty years, of mechanical excavation in its various forms—face-shovel, dragline, bucket-dredger, suction dredger—to say nothing of the now ubiquitous bulldozer and scraper for 'muck-shifting', has revolutionised production.

Between the two wars, the total number of quarries in Great Britain remained relatively stable, fluctuating round about 6000; during the same period however the output of quarried minerals increased by 300 per cent, from 35 million tons (in 1922) to nearly 105 million tons (in 1937). Since the last war the figures have been even more spectacular; output of quarried minerals has risen to over 180 million tons, whilst the number of quarries has declined to about 4650. The accompanying Table shows that the most remarkable increases over four decades have been in gravel, limestone, chalk and clay, with gravel and sand output having actually multiplied more than 30 times. The reason is not far to seek. We are now living in an age of concrete, the raw materials for which are cement (made from chalk or limestone, usually with clay added) and an aggregate composed of sand and gravel. Thus it is in large measure a technical change in the use of the minerals which is responsible for generating the demand; the engineers have responded to the challenge by making the increased output possible with mechanical aids—in other words, by 'bigger and better holes in the ground'.

Two examples will suffice to show what has been happening. Before World War I the Jurassic ironstone fields of the East Midlands were characterised by shallow quarries in which an overburden of not more than 15 ft. or so, and frequently less,

OUTPUT OF MINERALS IN GREAT BRITAIN
(in million tons)

Mineral	*1922*	*1937*	*1959*
Ironstone	4·5	10·9	14·9
Igneous rocks	6·0	10·5	14·3
Limestone	9·4	19·0	35·8
Chalk	3·0	10·2	14·9
Clay and shale	6·4	25·6	27·8
Sand and gravel	2·0	20·4	63·7*

* The 1960 figure was 76·2.

was removed by hand to uncover the ironstone seam, which was also dug and loaded by men with picks, forks and shovels. The soil was carefully stripped, and replaced on the worked-out ground so that agricultural restoration was complete. As the workings advanced into deeper overburden—say 20 to 30 ft.—mechanical face-shovels were employed to remove the overburden, but in many cases the surface soil was still stripped by hand and wheeled across the quarry on planks resting on tall trestles, to be replaced on the levelled overburden heaps behind the advancing face. There came a depth beyond which it was impracticable to 'walk the plank' with barrows of soil, and the increasing expense of hand labour, with the economies to be reaped from mechanisation, put an end to this practice and also, in general, to the retention of the top-soil and to the levelling out of the overburden heaps which grew in parallel ridges ('hill-and-dale') behind a fixed-boom face-shovel. So with overburdens increasing to 50 ft. or more, the problem of land devastation was created which prompted the appointment of the Kennet Committee in 1938.[3] This Committee, faced with nearly 3000 acres of derelict land in Northamptonshire and adjoining counties, was unable to suggest very much other than afforestation as a means of restoring the ironstone land to some economic use. But something like a technical revolution occurred during the war in respect of the machines available for 'muck-shifting' and for excavation and levelling, and after the war the problem appeared a much more tractable one, for the machines which were capable of far greater devastation of the land than ever before were also capable of helping to repair the damage. The tractor-drawn scraper made separate soil stripping a practical proposition; the bulldozer greatly assisted in the task of levelling the heaps of overburden, and the introduction of the walking dragline made possible, in certain

circumstances (actually in overburden of no more than about 35 to 40 ft.) the avoidance of 'hill-and-dale' and the immediate creation of level overburden surfaces on which the separately stripped top-soil could be replaced.[4] Considerable advances were also made in the techniques of afforestation, and also in the difficult task of re-creating an agriculturally usable soil from the levelled overburden when the original soil had been irretrievably lost. So, although overburden thicknesses of up to 80 or 100 ft. are now removed in some of the quarries, the technical aids now available are such that the problem has been effectively solved—and of course the financial aspect of it has been controlled by legislation, in the Mineral Workings Act of 1951.

A second example of technical changes is provided by the gravel industry. Before World War I the average gravel pit was almost a one-man affair, and operations were severely restricted to those deposits which lay above the level of the subsurface water table. The introduction of the face-shovel and the dragline, as in the case of ironstone and other quarries, has enabled much greater thicknesses to be worked and much greater outputs to be obtained, whilst the use of draglines, bucket-dredgers and suction-dredgers has rendered possible the large-scale excavation of low-lying terrace gravels from beneath the water level—with of course the resultant formation of lagoons which provide one of the most serious problems in the whole field of conflict between mineral working and other forms of land use. As in the case of ironstone, the bulldozers, scrapers and draglines can be used to reinstate level surfaces, but the filling of the holes, and particularly of the lagoons, is dependent on the availability of suitable materials. This is in large measure simply a question of economics—are the holes near enough to the source of rubbish or other material which has to be disposed of, to make it worth the disposer's while to use them rather than other possible dumping grounds? But again technical factors are involved, for it is still considered inadvisable to dump crude domestic refuse, which is in abundant supply around every urban area and creates many problems of disposal, into the lagoons, for fear of polluting both the water and the atmosphere. Nevertheless, experimentation has shown that even this is now possible, and further advances in the techniques employed for aerating the water and so preventing pollution may solve two problems at once, the Local Authorities' problem of refuse disposal and the gravel operators' problem of re-creating a usable land surface.

Thus, in terms of my original classification of environmental factors, the ironstone and gravel industries have shown a marked change in the *process* of land occupation, due to advancing techniques; and these techniques, by rendering accessible minerals which half a century ago would have been inaccessible, have altered the relative value of the land for other purposes such as agriculture and building, and incidentally, have materially altered what I might term the 'cultural landscape' of mineral working.

Turning to the field of mineral utilisation, technical advances may have considerable influence on the relative importance of different minerals or of different varieties of the same mineral. Outstanding examples of this are to be found in the iron and steel industry. In the early eighteenth century the Wealden ironstones of Kent and Sussex, and the haematites of the Forest of Dean, were our main sources of iron ore, since here alone were timber resources adequate to feed the charcoal furnaces. The introduction of smelting by coal and coke in the second half of the century caused the concentration of iron smelting on those coalfields where coals suitable for coking by the 'hearth' method, and also ironstones, occurred in the same series of Coal Measures—as in Shropshire, north and south Staffordshire, Derbyshire and south Yorkshire, and north-eastern South Wales, for example.[6] The development of the technique of hot-blast smelting in 1829 enabled the blackband ores of Lanarkshire to be more effectively utilised with raw 'splint' coal as a fuel, and thus gave a fillip to the industry in that area, and later to the eastern part of the north Staffordshire coalfield where similar blackband ores were smelted with locally produced coke.

The introduction of the beehive coking process, using strongly-swelling or 'caking' coals of higher rank than the 'clod' types used for the hearth process, upset the balance somewhat, for some of the early centres of iron smelting, like the Black Country, had no caking coals available; other areas, like north Derbyshire and south Yorkshire, had both types, but the greatest beehive coke area of

all—south-west Durham—had virtually no iron ores, and its full development had to await the 'discovery' of the Jurassic ores.

The use of the Jurassic ironstones after 1850 introduced a whole set of new geographical values. These ores were slightly leaner than the Coal Measures ironstones, but they were much more readily accessible; and moreover technological advances in blast furnace construction and operation had so reduced fuel consumption that it was just as economic to send coke to the orefields—as at Middlesbrough, Scunthorpe and Wellingborough, for example—as to send Jurassic ores to the older coalfield smelting centres.

The next technical revolution came in the third quarter of the nineteenth century, with the introduction of the Bessemer converter and the Siemens open-hearth furnace. Several aspects of these processes had important geographical consequences. In the first place neither of them could use anything but non-phosphoric iron made from haematite ores, for with the silica furnace linings which they used there was no possibility of eliminating phosphorus during the conversion from iron into steel. Two results accrued. The first was the considerable stimulation of haematite mining in the Cumberland and Furness districts which possessed the only considerable deposits of this type of ore in the country; and accompanying this was the expansion of the smelting industry on these orefields and at the adjacent coastal ports such as Workington and Barrow. This was a less simple development than might have been expected, for the Cumberland coals did not make good coke and Durham coke had to be sent by rail across the Pennines by the 1400 ft. Stainmore Pass railway. The second result was the necessity to import foreign non-phosphoric ores—mainly from northern Spain and central Sweden—and this emphasised the importance of coastal or near-coastal sites such as Middlesbrough and the South Wales smelting towns such as Merthyr Tydfil and Ebbw Vale.

Another consequence of the introduction of the two steel processes arose from differences between them, especially the adaptability of the open hearth furnace for the use of scrap metal. Whereas the Bessemer converter worked best with new hot metal, the Siemens furnace could use an appreciable proportion of scrap, so much so that the availability of scrap as a raw material became a new localising factor in the steel industry, not only attracting the industry to areas where engineering and shipbuilding provided much scrap metal, but also enabling the industry to set itself up on sites and in locations away from blast furnaces—as it did in Lanarkshire, for example, and in western South Wales (where, in the Swansea–Llanelly district, it was associated with the tinplate industry which provided both a market for sheet steel and to a certain extent a source of scrap).

A further technical development in 1879—the introduction of the Thomas-Gilchrist 'basic process'—opened up a further series of possibilities for the iron and steel industry, making it possible not only to use the Jurassic ironstones for steel-making but also to import richer foreign phosphoric ores. In actual fact the momentum of acid steel production was such that the basic process did not immediately revolutionise the industry as it did in Lorraine or in the Ruhr, and it was not until the First World War that the output of basic steel exceeded that of acid steel. Since then however the basic open-hearth process has almost completely dominated the industry, and this has given a stimulus, first to the orefields, as at Scunthorpe and Corby, and secondly to coastal locations such as Middlesbrough, Cardiff and Port Talbot where the foreign ores arrive.

The Bessemer process, however, survives in two forms. First, the only remaining 'acid Bessemer' plant in the country is at Workington, still in part dependent on the Cumberland haematites but largely on imported ores. Secondly, the 'basic Bessemer' process, after dying out completely in the 1920s, has been revived at several places, such as Corby and Ebbw Vale, where the siliceous and phosphoric Northamptonshire ores are employed in the blast furnaces and the steel is treated in 'hot-strip mills' for the production of narrow strip for steel tubes or wider strip for tinplate manufacture. The cheapness of the Bessemer process (which uses no extra fuel) for the production of the less highly specialised grades of mild steel is a great attraction in localities which are either far from coal (like Corby) or far from ore and in relatively inferior geographical situations (like Ebbw Vale), whilst the high phosphorus content of the Northamptonshire ore renders it the most suitable of all the Jurassic ores for this process.

Incidentally, the effect of the mass-production of sheet steel and tinplate at Ebbw Vale, and more recently at Margam as well (with its associated cold-rolling and tinning plants at Velindre and Trostre) has been virtually to extinguish the older tinplate works in South Wales, with some of the associated steel works. Truly, technical advance benefits some but not others. Fortunately, however, there have been no Luddite riots in South Wales as there were when mechanisation replaced hand working in the Lancashire cotton industry a century and a half ago!

A last technical feature of the iron and steel industry in the twentieth century is the development of the by-product coke oven, and with it the possibility of vertical integration, with all the heat and energy economies resulting therefrom. Not only are the by-products valuable in themselves, but the waste gases from the coke ovens, often combined with the waste gases from the blast furnaces, can be used for heating the air blast, for firing the open-hearth furnaces, and for generating electric current to drive all the machinery—the blowing engines, the charging mechanism and the rolling mills. The vast size of such integrated works, however, and their rail transport requirements (which may easily reach 100,000 tons a week), create siting problems of considerable magnitude, and the number of possible future locations for such plants, now that Ravenscraig, near Motherwell, is nearing completion and the new 'Spencer' works at Newport is well on the way, must be very small indeed.

So much for iron and steel. I have said nothing new. I have simply tried to emphasise that explanations of the industry which fail to take full cognisance of the nature of the technical processes do less than justice to the subject. And I hope I have shown how the relative value of different ore and coal deposits, and of different types of site and location in relation to raw materials, fuel, ports and markets have changed markedly and often, in response to the technical changes within the industry.

I turn now to a brief examination of the *economic environment*. This, I suggest, includes three aspects. In the first place there is the general national and international economic situation, with its trade cycles, its booms and depressions, and the upsets due to wars. Different sections of the mineral industries are affected in different ways by these trade fluctuations, and it may perhaps suffice to recall the fairly rapid extinction of the greater part of our lead-mining industry which accompanied the great increase in the imports of cheaper Spanish ores after about 1870; the grievous repercussions on our coal-mining industry, especially in South Wales and in Durham, of the increasing use of oil in the world's shipping, and of the competition, in the 1920s, of Polish coal; and the stimulation of open-cast ironstone mining in the Jurassic fields during the last war, when our foreign supplies were almost completely cut off.

Secondly, there is the relation between the mineral-producing industries and the industries which convert the minerals into finished goods of one sort or another. This is essentially a price relationship. The mines and quarries must sell their coal, ores or rocks at a price which the consuming industries can afford to pay, having regard to their other raw material, fuel and labour costs and to the ultimate price of the final products. A delicate balance is thus maintained, and any alteration of the relationship may have important consequences for the mines and quarries, whose costs of production are intimately related to the geological circumstances under which they have to operate, and to the technical means of production at their disposal. A rise in price at the production end might result in consuming industries being prepared to use lower quality materials in order to keep their costs down, or seeking substitute materials. The matter is clearly of the greatest significance in those areas where possible competing materials exist in close proximity—as gravel and crushed stone, both sources of concrete aggregate, do in parts of the Midlands, for example, or as oil (from Llandarcy) and coke do in the steel-making district of South Wales.

A third aspect is that of transport costs which, in the case of the mineral industries, loom very large because of the great bulk and relatively low value of their output. There are several points of interest here, including the medium of transport commonly employed, the distance which the mineral can travel without becoming too expensive for its consumers, and the nature of the market for the mineral. It will be most convenient to study these by actual examples.

Taking first the case of gravel, the salient points are as follows:

(i) that the pit-head price is very low, averaging perhaps 12*s.* per cubic yard;
(ii) that the market is mainly in building, road-making and civil engineering jobs of many different kinds, which are constantly changing in detailed location and which demand numerous grades of sand and gravel for different purposes;
(iii) that the life of a gravel pit is relatively short, so that it is rare to find one which has access to a railway line or to a navigable waterway;
(iv) that in consequence of (ii) and (iii), road transport is generally employed, which can secure not only 'pit-to-site' transport of the gravel but also the most rapid turn-round, and so the most economical use of vehicles;
(v) that, since the cost of road transport is about 8*d.* per cubic yard per mile; (though the first mile, which includes loading costs, may cost 2*s.*) the price of the gravel has doubled after a 16-mile journey, and the economic limit has in most cases been reached before a distance of 30 miles from the pit has been attained—though this distance will clearly vary with the quality (and price) of the gravel and with the availability, near the economic margin, of alternative supplies. In this connection it is fortunate indeed that there are relatively few areas, at any rate in England, which are more than 30 miles from one source of gravel or another.

Occasional examples of longer-than-average movements are due to special circumstances. Thus the south Lancashire district is notably deficient in large supplies of good gravel, and considerable movement of high-quality quartzite gravel from the Bunter Pebble Beds of north Staffordshire takes place, and of river gravels from the Wakefield district. Again, gravel moves into Merseyside from the Wrexham area of north-east Wales; whilst on the eastern side of the country the existence of the navigable river Trent, which has a rich gravel field along its terraces in Nottinghamshire, makes it possible for pits in the Newark district to send to the Humberside market.

As a second example, the Jurassic ironstones offer some interesting contrasts with gravel. Worked in many cases under much more difficult geological circumstances and from beneath thick overburden, their selling price is in general lower than that of gravel. Yet, whilst it is true that a fair proportion of the output is used quite close to its source—at Scunthorpe, Corby and Wellingborough for example—a substantial tonnage also moves away by rail from the orefields of Northamptonshire and south Lincolnshire into Derbyshire, Staffordshire and even as far afield as Middlesbrough and South Wales. The reasons would seem to be:

(i) that, in contrast to gravel, which is widespread and of frequent occurrence, ironstone is restricted to a very few localities;
(ii) that the quarries are very large and have standard-gauge railway tracks in them;
(iii) that much of the smelting plant is located on the coalfields, where coal transport costs are low, or at ports where foreign iron ores can also be obtained;
(iv) that these destination points are fixed and constant, and in consequence ore can move at regular intervals and in whole train-loads —facts which will be reflected in the rates charged by the railways;
(v) that the end-product of ironstone is finished steel, which is very much more valuable than an equivalent weight of concrete; the cost of ore transport thus represents but a small fraction of the final cost.

A third example will serve to conclude this rather lengthy treatment of the mineral industries; and I use it because it illustrates a number of important points besides the merely economic ones. It is the brick industry.

Brick-making clays are found in every geological formation from Ordovician to Recent, and are very widespread in occurrence. Brickworks are almost invariably situated alongside the clay pits which supply their raw material, and since their market is the urbanised areas of the country it is not surprising that the map of brickworks, up to the Second World War, bore more than a passing resemblance to the population map.[7] Bricks seldom travelled far in the period before the First World War, and much of the fascinating variety of appearance of our towns and villages is due to the different colours and textures of the

locally-produced brickwork. London's yellow 'stock' bricks were made from the brickearth of the Thames terraces, mixed with dustbin refuse, the ashes from which helped the firing (and can still often be seen in individual bricks). Shiny 'Accrington reds' characterise the cotton-mill towns of south Lancashire, pinkish-red bricks the Keuper Marl districts of the Midlands, and so on. Only the famous 'Staffordshire blues'—the structural engineering material of the pre-concrete age—were to be found far from their home in the Black Country and north Staffordshire, employed in canal aqueducts and railway bridges.

In the late 1930s there were some 1200 brickworks in England and Wales, scattered through fifty counties. In many of these the clay was still hand-dug, and sometimes the bricks too were handmade. Technical advances in mass-production, however, both of the raw clay by mechanical excavation and of the finished bricks by the 'semi-dry-press' process, had succeeded in concentrating one-third of the brick production into about 30 large works situated on the Oxford Clay formation in a belt stretching from Peterborough to Oxfordshire, with concentrations particularly near Peterborough, Bedford and Bletchley.[8] The reasons for this remarkable concentration are physical, technical and economic. The Oxford Clay is a thick and relatively homogeneous formation, which lends itself readily to excavation by large machines —face-shovels and draglines, or bucket-chain excavators—in great contrast, for example, to the Etruria Marl formation of north Staffordshire, which still has to be hand dug because of the necessity to select the best seams of clay. Moreover, the clay contains finely-divided carbonaceous matter of vegetable origin, and this burns during the firing of the brick, thus helping to reduce the fuel consumption in the kilns.* The process employed is the semi-dry-press. The clay, which is but slightly plastic, is ground to a fine grade, and masses of ground clay, just moist but not wet, are pressed into brick shape by powerful presses (the trade name 'Phorpres'—four-press—refers to this). The possibilities for mass-production (each press can produce well over a thousand bricks an hour) are thus enormous—which brings us to the economic point. The economies of large-scale production and very low fuel consumption are such that Oxford Clay bricks—known generally as 'Flettons' from the village of that name near Peterborough—can stand much higher transport costs than most other bricks. Moreover, most of the big works are alongside the mainline railways that cross the Great Clay Vale on their way from London to the Midlands, or on the transverse line that runs through the Vale and crosses each of the main lines in turn. Between the wars the greater part of London's suburban expansion, especially north of the Thames, was effected with these pale pink bricks, and a highly-organised rail and road distribution system enabled them to penetrate even into established brick-making areas as far afield as Durham and south Lancashire.

Since the last war the concentration has become even more marked. More than 600 local brickworks have been closed (the 1958 Census of Production records only 525 brickworks) and over one-half of the national brick output is now of 'Fletton' type (54 per cent in 1958). Thus the combination of exceptionally favourable physical circumstances, technical progress and a high degree of economic organisation have combined to put a very different face on Britain's buildings from that which characterised the nineteenth century. One striking recent example may be quoted. In 1960 twelve blocks of flats, using nearly a million-and-a-half 'Phorpres' bricks from Stewartby, Bedfordshire, were built in Salford; within a 20-mile radius of Salford there were no fewer than 80 brickworks in 1939.

I should like now to consider one or two other examples of the geographical consequences of changing industrial techniques.

One of the most potent of all the influences on industrialisation has been the location of sources of power and heat. Even before the Industrial Revolution there was some tendency for the woollen industry, for example, to locate itself in sheep-rearing areas where water wheels could work fulling mills—as in the West of England, on the Pennine flanks in Yorkshire and on the fringes of the Lake District—and it is noteworthy that the early worsted industry, in which the fulling process was unnecessary, established itself in East Anglia

*The fuel consumption in the 'Fletton' brick industry is about ¼ cwt. of coal per ton of bricks. The average for the rest of the 'Common brick' industry is about 1¾ cwt., and for the highest quality engineering bricks it may rise to 4 cwt.[9]

where water power was almost absent. The first part of the Industrial Revolution added much emphasis to water power, for the early cotton machinery of Arkwright and Crompton, for example, was first powered in this way. But the development of the steam engine after the 1770s placed the emphasis firmly on a supply of coal, both for power, as in the case of the textile industries, and for heat, as in the iron industry. The largely twentieth-century development of the use of electricity for heat and for power has contributed two noteworthy new features to the industrial map, first the location of hydro-electric stations and their attendant special industries, in hitherto completely un-industrialised areas, and secondly, through the development of transmission networks, the outward spread of industrialisation away from the coalfield areas in which it was mainly concentrated during the nineteenth century. Two interesting facets of this are the development of aluminium smelting, and the new post-war pattern of electrical generation.

The ore of aluminium is bauxite, and this is first purified to alumina, not necessarily either on the orefield or at the locality where the smelting is to take place. In Great Britain the ports of Burntisland and Newport are the centres, at each of which coal is readily available to provide heat for the process. But the smelting is done at Fort William and Kinlochleven, where there are hydro-electric stations. There is a simple reason for this—which curiously enough never seems to get into the geography textbooks. It is that very high intensity but low voltage *direct* current is required to provide the *heat* for smelting. At Kinlochleven the cells in which the alumina is dissolved in molten cryolite at about 1000° C. run at 5 volts with current of 40,000 amperes; at Lochaber works, Fort William, 100,000 amperes. About 8 KWh. of energy are needed to produce 1 lb. of aluminium, or 18–20,000 KWh. per ton. Here lies the problem, for the transmission of electricity by cable over long distances is commonly accomplished by using very high voltage but low intensity *alternating* current, and the technical difficulties involved in transmitting direct current have not yet been overcome. So aluminium smelting is very effectively tied to the generating stations, and the current requirements are so large that it is always hydro-electric stations that are involved. It is perhaps worthwhile emphasising that it is not *power* which is required but *heat*.

The changes which have come over thermal electric generation and transmission since the last war have been effectively analysed by Mr. E. M. Rawstron and I need do no more than refer to his work.[10] The changes are a response to several technical and economic stimuli: first, the enormous expansion in electricity consumption, both industrially and domestically, second, the economies to be reaped from increased size in the generating stations, involving the use of powdered coal fuel and enormous quantities of water, thirdly, the economies derivable from very high voltage transmission. Thus, whereas the early pattern of generating stations followed largely the distribution of urban population, with many separate local transmission systems, a second stage involved the creation of the national electricity grid, and a third stage, since the war, has been concerned with the creation of great new power stations located perhaps more with regard to water supplies and ash disposal than to coal supplies or urban populations, and the establishment of a 275,000 volt 'super-grid'. The two types of station location which have been developed are (*a*) along the river Trent, where the supply of cooling water is abundant enough for cooling towers to be largely if not entirely dispensed with, and where in addition the most cheaply mined coal in the country is available from the Nottinghamshire coalfield; (*b*) in coastal situations where sea-water can be used, with coastwise coal supplies, or oil fuel.

Here it is perhaps appropriate to interject a general principle. Do not the examples so far given of the consequences of technical advancement begin to lead to the conclusion that, rather than emancipating man from the influence of the geographical environment, the increasing scale and complexity of industrial technique offer a progressively narrowing range of locational possibilities? Domestic wool-working could take place more or less anywhere; water power confined it much more narrowly, whilst steam power narrowed the range still further. Iron smelting with coke had a much narrower range than in the days when charcoal was used; the invention of acid steel processes considerably narrowed the range of possible locations, whilst the modern trend for vast

integrated works leaves but a mere handful of possibilities open. Aluminium smelting, at any rate in Britain, has an extremely narrow range of possibilities, and as thermal electric stations increase in size and complexity so there is a decreasing number of possible sites available.

Nuclear power stations are even more exacting in their requirements, for although they are virtually emancipated from control by the location of their fuel supplies, they have to fill gaps in the existing pattern of thermal generating plants and their detailed siting is fairly rigidly controlled by their water supply needs and by the policy of utilising rural sites far from the major urban concentrations.[11] It is not surprising in this densely populated island that difficulties are being experienced in finding suitable sites.

Further examples of this can be found in the oil industry which has undergone a remarkable transformation during the post-war period. In 1938, some 2·4 million tons of crude oil passed through British refineries, and the total was only fractionally greater in 1947; by 1959, however, the figure had risen to 39 million tons. The reasons are economic and political as well as technical—such as the dollar shortage, the troubles in Persia, and the fact that it costs less to import crude oil in large tankers than to import separately the great variety of petroleum products which are now required by different forms of transport and prime movers. Two major technical developments have also been concerned. The first is the considerable growth of the new petrochemical industries, which produce, as derivatives from the oil refining processes, the basic materials for the manufacture of certain types of plastics (such as polythene) and of man-made fibres (such as nylon and terylene). Clearly such industries are most appropriately associated with the refineries, and British industrial progress would now be somewhat hampered without them. The second is the transformation of the ocean tanker from the characteristic 12,000-ton vessel of the 1930s, first to the 20–30,000 tonners of the late 1940s and more recently, particularly since the Suez 'affair' of 1956, to the 'super tankers' of anything from 40,000 to 100,000 tons capacity.

Oil refineries must clearly be coastal in location; they are apt to be unpleasant neighbours and so the immediate vicinity of large ports and urban areas must be avoided. Situations on the major estuarine shores are thus indicated—e.g. the Thames, Southampton Water, the Mersey and the Forth. Physical circumstances and the existing pattern of land use have so far ruled out the Tyne and the Clyde, and distance from the major centres of consumption has ruled out the deep-water harbours of south-west England. When it comes to selecting new sites which can be reached by 100,000-ton tankers and at the same time are reasonably accessible to the consuming areas, the industry is faced with increasing difficulty. The refinery at Grangemouth is already supplied by a 57-mile pipeline from Finnart on Loch Long, because of the shallowness of the Forth estuary; a new pier for supertankers has been built on the Mersey so that oil can be piped to the Stanlow refinery on the Manchester Ship Canal; and now, because of the colossal expense of enlarging Queen's Dock, Swansea, to take supertankers, the Llandarcy refinery has a pipeline from Milford Haven, where the new oil terminal is also to have an 'Esso' refinery attached. After Milford Haven—where next? Another Fawley on the eastern side of Southampton Water has been strongly opposed on planning grounds. The supertanker has certainly narrowed the possible range of new sites almost to vanishing point.

It would clearly be possible to go on multiplying these examples of changing geographical values resulting from changing industrial techniques. The field of transport obviously presents enough material in itself for a whole series of lectures and I can only throw out a few suggestions. First, the impact of the introduction of refrigeration and temperature control into ocean shipping on the agricultural economies of Australia, New Zealand, Argentina, Jamaica and many other countries. Second, the vast range of consequences of the internal combustion engine, the diesel engine and the pneumatic tyre on the nature of freight and passenger movement by road, and on the oil industry. Third, the development of air transport which has opened up a vast new field of geographical studies, only the fringe of which has yet been touched by geographers.[12]

I will conclude with a few observations on one aspect of the second of these, namely the motor industry, which presents some interesting examples of locational principles. Here is an 'assembly'

industry with a very high rate of technical change, and thus a high rate of obsolescence of capital equipment; an industry which, though based originally on a high degree of mechanical skill, has succumbed to automation and mass-production; an industry moreover whose products are mobile in themselves.

The early industry was located almost entirely in the West Midlands, where it arose out of the cycle industry and was supported by the multifarious metal-working trades and skills of Birmingham and the Black Country, out of which grew the components industries of today. No other engineering district in the country had the variety of experience in ferrous and non-ferrous metals, and in precision work for such things as rifles and locks, that was present in this area, and the skilled labour was important when every car was a handmade job. The specialist car producers, like Jaguar and Rover, are still in the West Midlands, close to their sources of components and to their reservoir of skilled labour, and it is interesting to find Rolls-Royce first at Derby and then at Crewe, both towns the home of locomotive engineering.

The arrival of American flow-production techniques in the 1920s altered the situation appreciably. Specialised machine-tools and automatic transfer machines began to reduce both the labour requirements per unit of output and also the degree of skill required from a large proportion of the labour. The pull of the components remained strong—far stronger than the supply of sheet steel, which, coming largely from South Wales, has never in fact had any influence at all—so that Coventry and Birmingham remain very much in the picture. But assembly plants came into existence at Oxford, at Luton and at Dagenham, each for different detailed reasons, though all on 'virgin' sites and with no accompanying reservoir of skilled labour or component manufacture. The fact that in recent years the Government has been exploring the possibility of persuading the motor industry to set up assembly plants in the Development Areas of South Wales and Scotland, and that two of the 'Big Five' have agreed to establish themselves on Merseyside, is an indication that car-assembly has almost, in fact, become a 'footloose' industry. It is fortunate that the components industries are all more or less centrally situated in the country, so that in a sense any of the four estuarine areas would have served—but Merseyside, by reason of its shipping facilities, was clearly the best bet, London being ruled out on planning grounds.

From these miscellaneous and sometimes detailed examples which I have given of changing industrial techniques and their geographical consequences, I hope that one major conclusion will emerge, namely, that it is impossible to appreciate the geography of industry without knowing something, and sometimes quite a lot, about the industries themselves, about their raw materials and the processes by which these are transformed into the end-products, which may be either themselves saleable as 'consumer goods' or form the raw materials or components for another industry. Just as in the study of agricultural geography (and I realise that I have said nothing about the changing techniques of farming) it is necessary for the student to visit actual farms of various kinds in order to appreciate the relation of the operations to the physical, social and economic environment, so, I submit, an intensive programme of factory and works visits is necessary to complete the geographer's education on this aspect of economic geography. It is possible, of course, to read the technical literature in an arm-chair, but it is so much better to see for oneself, and to know exactly what goes on inside an iron and steel works, or a textile mill, or a motor car factory; and small establishments as well as large ones should be included, old as well as ultra-modern. I sometimes feel that our field-classes spend too much time looking for doubtful erosion surfaces when they might be better employed in understanding the how and why of the manufacturing industry by which the majority of our people earn their living.

So, in conclusion, to return to the trilogy with which I began. The British people have been favoured by a highly complex ethnic structure which gives a wide variety of physical and mental characteristics, and by a climate which is possibly more conducive to constant and sustained effort than any other in the world. They have developed through the centuries processes of land occupation and resource development which have been greatly influenced and aided by technical advances, and these latter have so often found some part of the varied environment of Britain, with its extraordinary variety of geological formation and its

considerable ranges of relief and climatic characterisation, exceptionally appropriate to their requirements. As the history of human occupance in Britain is a long one, and as we were first in the field of industrialisation, the product, in terms of the cultural landscape, is an appearance of old age. But the extraordinary technical revolution of the twentieth century has produced a remarkable rejuvenation, to which our exploding conurbations, our new pattern of thermal and hydro-electric and atomic power, our new industrial distributions, our motorways and our coastal caravans, all bear eloquent testimony.

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ECHOES from the Past

Inflammatory Questions

'Whatever the objects of the founders of the Association may have been, it is obvious that questions of public importance could not be permanently excluded from meetings the success of which depended on the interest stimulated in the community. The Statistical Section, which owed its origin to the visit, at the first Oxford Meeting (1832), of Quetelet, the Belgian astronomer and economist, was the first to assert itself by engaging in a discussion of the Poor Laws. Whewell deeply resented this violation of academic neutrality: "it was impossible," he wrote, "to listen to the Proceedings of the Statistical Section on Friday without perceiving that they involved exactly what it was most necessary and most desired to exclude from our Proceedings," and again: "Who would propose (I put it to Chalmers, and he allowed the proposal to be intolerable) an ambulatory body, composed partly of men of reputation and partly of a miscellaneous crowd, to go round year by year from town to town and at each place discuss the most inflammatory and agitating questions of the day?"

'Fortunately for our Association, this narrow-minded attitude did not prevail, and our records show that while not avoiding controversial and even inflammatory subjects, we have been able to exercise a powerful influence on the progress of science. The establishment of electric units, universally accepted throughout the world, originated in the work of one of our committees; the effort which led to the foundation of the National Physical Laboratory, one of the most efficient and beneficial organisations in the country, received its first impulses from us; and the organisation of the first world service for the systematic investigation of earth tremors was established by the late Dr. Milne, working through one of our Committees.'

Prof. Arthur Schüster, F.R.S., Presidential Address, Manchester, 1915.

* * *

Incombustible Cloth

'Specimens of incombustible cloth for ladies' and children's dresses, manufactured by Mr. James Latto, Dundee, were exhibited to the Section by Sir David Brewster. This cloth will not catch fire either by a spark or even by contact with a lighted candle, or fire to such an extent as to injure the person who wears a dress made of it. It burns slowly, with a greenish flame, and is speedily extinguished.

'Rain or washing deprives the cloth of its difficult combustibility, and it was with the view of directing the attention of chemists to the subject, so as to discover a method of giving the cloth a permanent incombustibility, that Mr. Latto was anxious to have his specimens submitted to the Section.'

James Latto, B.A. Meeting, 1849.

THE PHYSICAL PRINCIPLES OF SWITCHES AND CIRCUIT-BREAKERS

By Dr M. P. REECE *Electrical Research Association*

This article, based on the 1960 Kelvin Lecture, describes something of the physical principles of what is probably one of the most interesting of the more common electric circuit elements.

It is perhaps surprising that in these days of rapid scientific and technological advance, it is not yet possible to design electrical switchgear from anything approaching first principles. This applies to all switches, from the small domestic light switch on the wall to the largest circuit-breaker capable of controlling the power for a whole town.

This state of affairs is admirably demonstrated in the electrical engineering departments of our universities and technical colleges, where students are often required, as exercises, to design magnets, transformers, alternators and other pieces of electrical plant, but are never asked to design a switch or circuit-breaker.

The reason for this state of affairs is not very hard to find; switches almost invariably use an electric arc of one kind or another as the actual switching element, and it is the arc that presents an almost impossibly difficult task to the theorist.

It cannot be claimed that electric arcs are not yet quantitatively understood for lack of trying. Before nuclear physics became fashionable, many of the more gifted physicists used to research into gas discharges, and some very eminent names have been associated with the subject. No, the difficulties, as the people working on controlled thermonuclear reactions are finding, are fundamental, and arise primarily from the extreme complexity of the processes occurring in gas discharges.

This, then, is what makes switchgear such an interesting study. There are still problems of a basic nature to be solved, with the ultimate aim of putting ourselves in a position where we can design switches and circuit-breakers from first principles. We must, however, always keep in the back of our minds the possibility that we may not be successful and may have to go on in the same old empirical way. What is the objection to empiricism? The answer is simple: economics. Without quantitative theory, the building of large circuit-breakers is an expensive business, because of the immense amount of cut and try development required.

The Functions of a Circuit-breaker

Switches and circuit-breakers must permit or prevent the flow of current in the branch of an electric system in which they are connected. A switch need only be capable of starting or stopping the flow of current under normal conditions, whereas the circuit-breaker must be able to control the extra large currents which flow when lightning or other causes put short-circuits on a power system. The large 'fault' currents which may flow as a result of such short-circuits must be interrupted in the shortest possible time, not only to prevent damage to equipment, but also because in a tightly interconnected system, such as the British grid, too persistent a fault could cause electrical chaos throughout the country.

To introduce a few numbers, which make it easier to visualise what large modern circuit-breakers are called upon to do, a circuit-breaker rated at 15,000 MVA. (15.10^9 VA.) at 275 kV. must be able to interrupt peak currents somewhere in the region of 80,000 amp., and to withstand voltages across its open contacts of up to 400 kV. within milliseconds of interrupting the current. But then the same circuit-breaker must on other

occasions be capable of interrupting currents of a few amperes without producing dangerously high over-voltages.

Now let us consider what a circuit-breaker is. While the current is flowing, the closed circuit-breaker must present a very low impedance and when the circuit-breaker is open and the current interrupted, it must present an almost infinite impedance.

The term impedance, rather than resistance, is used deliberately, because in principle a switch could be a variable capacitor or a variable inductance. Nevertheless, the vast majority of switches and circuit-breakers take the form of variable resistors, having resistances of less than milliohms when closed, and more than thousands of megohms when open.

The next question to consider is how rapidly may the resistance of a switch or circuit-breaker be varied during the switching process. Fig. 1 shows a very simple direct current circuit containing an inductance, a switch, a load resistor and a source of e.m.f. in series. Starting with the switch open, assume that its resistance is suddenly reduced from infinity to zero. A current will start to flow, the initial rate of rise of the current being given by V/L, the final current being V/R. There is obviously nothing objectionable in this, so we may say that when closing a direct current circuit the resistance of the switch may fall to zero indefinitely fast without ill effect.

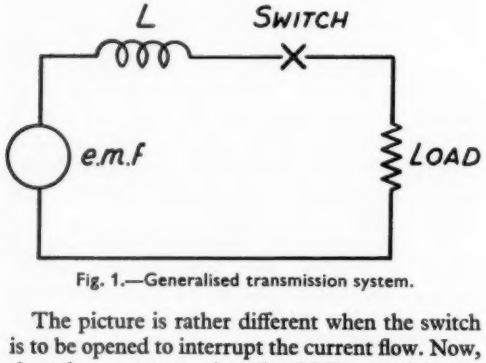


Fig. 1.—Generalised transmission system.

The picture is rather different when the switch is to be opened to interrupt the current flow. Now, there is an energy, given by $\frac{1}{2}LI^2$, stored in the inductance, and this energy must be dissipated in the resistance of the switch. Should the resistance of the switch increase too quickly, the resulting rapid fall of current would produce a voltage $-L(di/dt)$ across the inductance, and this voltage could damage the insulation of the circuit. It can be concluded, therefore, that when interrupting a direct current in an inductive circuit there is a limit to the rate at which the resistance of the switch may be allowed to rise.

In an alternating current system, the position is rather different. Fig. 2 shows a simple a.c. system. In switching on, it is found that, as in the d.c. case, the resistance of the circuit-breaker may fall indefinitely fast without giving rise to undesirable effects.

When the alternating current flowing in a system such as that shown in Fig. 2 has to be interrupted, the position is very different from the d.c. case. The basic difference is that with alternating current, the energy stored in the inductance is not constant but varies as I^2 varies, shuttling back and forth between the inductance and the power source. At the hundred instants per second when the current passes through zero, there is no energy stored in the inductance, and the resistance of the circuit-breaker could be increased from zero to infinity suddenly, without causing any undesirable high voltage. This process is shown in Fig. 2. Of course, unless the timing of the increase in resistance were absolutely accurate, so that it occurred at an instant when the current was naturally zero, very high induced voltages could result, as in the d.c. case.

The oscillogram in Fig. 2 shows the start and interruption of a fault current. The resistance of the circuit-breaker increases very rapidly at the fourth current-zero. When this happens, the voltage across the circuit-breaker approaches the system voltage via a transient oscillation between the inductance and the stray capacitance. This oscillation is called the restriking voltage.

To summarise, then, it can safely be said that a switch or circuit-breaker is merely a variable resistor with a very wide range of variation. When switching direct current, the resistance may fall rapidly as the switch is closed, but must increase relatively slowly when the switch is open; when switching alternating current, the resistance of the switch may fall suddenly and may also increase suddenly, providing that it does so at the correct instant.

To design such a device using physical resistors

made perhaps with metal or carbon, which could be increased at will from very low values to very high values and which, moreover, could be increased rapidly and at a specified instant in time, would be a very difficult job, but fortunately the electric arc can be made to function as such a resistor very satisfactorily. Not only can its resistance be made to vary over the very wide range required, but it may, by correct design of its environment, be made to change its resistance either slowly or very rapidly; and as if these merits were insufficient, it has one more vital property, that its resistance depends on the current flowing in it, so that it becomes self-timing when interrupting alternating current, increasing its resistance at the correct instant.

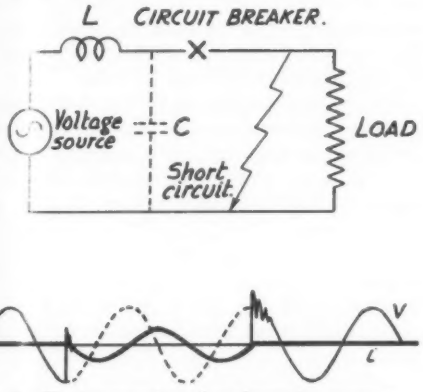


Fig. 2.—The interruption of an alternating current.

It is apparent, therefore, that the electric arc which forms naturally when metal contacts carrying current are separated, is almost the ideal variable resistor for switching. It has only one substantial disadvantage, and this is the difficulty of making electrical connections to it; having a temperature anywhere from about 6000° K. to 70,000° K., it does have an unfortunate tendency to burn up its terminals.

The Electric Arc

In most switches and circuit-breakers, the arc which forms the variable resistor burns in a gas, either at or above atmospheric pressure. There are a few exceptions, but the high pressure arc is the most common by far.

Gases at high pressures are normally good insulators, because the molecules or atoms of which they are composed are electrically neutral, and an electric field has little effect on the gas. To make it conduct, which it must if it is to work as a variable resistor in a switch, some of the outer electrons must be removed from at least some of the atoms or molecules, so that free charges, i.e. negatively charged electrons and positively charged ions are present in the gas; their movement under the action of an applied electric field constitutes a flow of current.

Electrons can be removed from their parent atoms or molecules in a number of ways. The particular removing, or as it is properly called ionising, process which is most important in high pressure arcs is thermal ionisation. This merely means that if a gas is heated to a sufficiently high temperature the kinetic energy of the thermal agitation of its constituent atoms or molecules becomes so large that at a substantial number of the impacts between colliding particles the collision is severe enough to knock an electron away from one of them. This is purely a thermal effect, and is not necessarily connected with any electrical process.

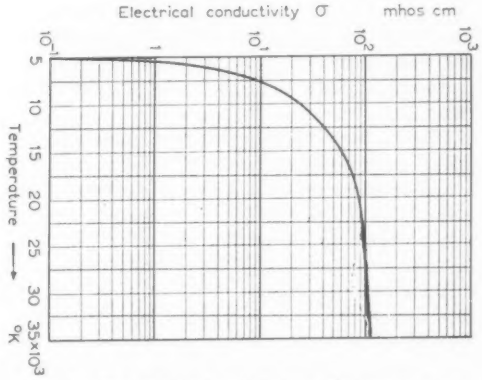


Fig. 3.—The electrical conductivity of nitrogen as a function of temperature.

The thermodynamics of thermal ionisation was elucidated by the Indian physicist, Saha, primarily in connection with his study of the atmospheres of the sun and stars, but the equation he deduced is also applicable to conditions in high pressure arcs. Saha's equation relates the fraction of gas atoms ionised to the ionisation potential, the

temperature and the pressure of the gas. From this and from the mobilities of the ions and electrons it is possible to compute the electrical conductivity of a gas as a function of its temperature. Fig. 3 shows a curve relating the conductivity and temperature of nitrogen at atmospheric pressure.

Imagine a cylindrical volume of air contained in a super furnace, capable of heating it up to, say, 6000° K. At this temperature the air will be quite a good conductor because some of its atoms are thermally ionised. If, now, two electrodes are inserted into the ends of this cylindrical volume, and a voltage applied between them, a current will flow. This current will itself heat the air even further, and if it is large enough the furnace can be removed with the air still remaining conducting, kept hot by the electrical power being dissipated in it. This is, of course, an electric arc.

Luckily, to form such an arc it is not necessary to use a furnace for the initial heating. The separation of two conductors carrying a current can do the initial heating and start an arc.

A continuous supply of energy is necessary to keep the arc in being because of the heat loss, largely by convection from its surface. Thus, if the current flowing in the arc is suddenly stopped, the temperature of the air will fall, the positive ions and electrons will recombine to form neutral particles and the gas will rapidly revert to an insulating state.

It has already been stated that the resistance of an arc depends upon the current flowing in it. The actual relationship in real arcs is complex in the extreme and depends on many factors, some of which cannot yet be handled theoretically. Nevertheless, a very simple physical model suffices to demonstrate the general trend. If it is assumed that the arc burns at a constant current density, $\mathcal{J}$ amp/cm^2 and suffers a heat loss of W joules/cm^2/sec. from its cylindrical surface, then, by equating the electrical power input to the heat loss, we have:

$$I = \frac{\mathcal{J}\pi D^2}{4} \quad \text{and} \quad D = \sqrt{\left(\frac{4I}{\mathcal{J}\pi}\right)}$$

$$\text{Hence: } V = \frac{1}{\sqrt{I}}\left[2W\sqrt{\left(\frac{\pi}{\mathcal{J}}\right)}\right]$$

$$\text{and: } R = \frac{1}{I^{3/2}}\left[2W\sqrt{\left(\frac{\pi}{\mathcal{J}}\right)}\right]$$

Thus, the resistance per unit length of arc is small when the current is large, large when the current is small and infinite when the current is zero. These are just the properties required for the resistor in a switch, since the resistance of the arc increases automatically to infinity as the current flowing falls to zero. Unfortunately there is a snag.

The snag is that the resistance of the arc cannot follow changes of current without a slight delay, so that when the current reaches zero, the resistance of the arc is not infinite, and the restriking voltage which then appears across the switch may be able to put back enough energy into the arc to cause it to revert to a conductor once again.

There are two reasons for this delay. Firstly, the arc contains stored thermal energy and therefore it takes a finite time to cool down, and secondly, even if the gas could cool instantaneously, the ions and electrons would still take a finite time to recombine to form neutral atoms.

The actual processes of cooling and de-ionising arcs are very complicated but again a simple model demonstrates the trend. It is assumed that in its last moments, as the current falls to zero, the diameter of the arc does not shrink, but the whole channel cools.

If K = heat stored per unit length of arc per degree above ambient, D = arc diameter, W = heat dissipated per unit length of arc per degree above ambient, then for the freely cooling arc we have:

$$WT + K\frac{dT}{dt} = 0$$

Hence: $T = T_0\varepsilon^{-Wt/K}$

Hence: K/W is thermal time constant of the arc.

Now K is proportional to D^2 and W is proportional to D,

$$\therefore \frac{K}{W} \text{ is proportional to } D.$$

If the resistance of the arc is to rise as rapidly as possible as the current falls to zero, the arc diameter must be small; it is one of the jobs of the circuit-breaker designer to reduce this delay to a minimum, by increasing the ratio of the heat loss from the arc to its stored energy.

Switches and Circuit-breakers

In the early days of electrical power distribution, voltages and currents were small and simple knife

switches, in which a pivoted copper blade swinging about one end could be pushed down into a gripping socket, were used for circuit-breaking. Originally, these switches were operated by hand and sometimes drew out long arcs which were alarming and could be dangerous when short-circuit currents had to be interrupted. The resistance necessary to secure interruption of the circuit was obtained mainly by the long length of arc drawn, and not by any very rapid change in resistance per unit length.

operated by the oil flowing in between the contacts at current zero and thus prevented re-ignition of the arc. Investigation with a high-speed camera, however, showed that the arc actually burned in a bubble of gas which remained between the contacts for some time after the arc was extinguished. Chemical analysis showed that this gas was largely hydrogen, formed by the cracking of the oil. The improvement in performance obtained by surrounding the arc with oil was due to the hydrogen, which, having a high thermal

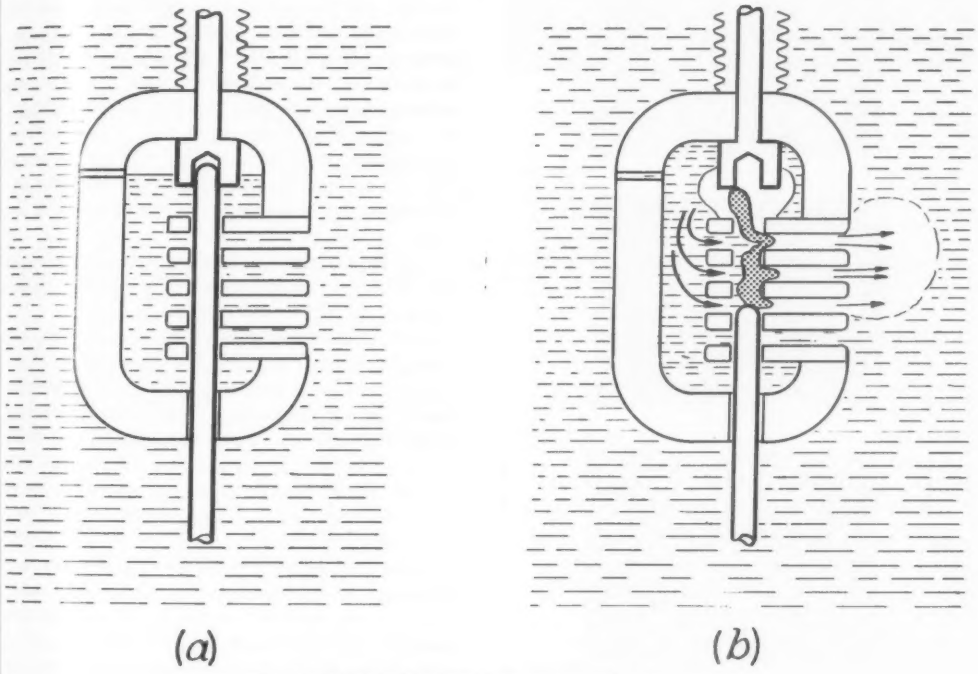


Fig. 4.—Principle of operation of arc control structure.

As higher voltages were used this type of switch became quite unable to deal with short-circuit currents, and the oil circuit-breaker began to come into use. The early oil circuit-breakers were little more than the old air-break switches immersed in mineral oil in a metal tank, and for a while these switches were able to cope with the steadily increasing short-circuit energies.

It was thought at the time that these switches

conductivity, increased W/K and shortened the time constant.

As power system voltages and currents continued to grow, some improvement in the design of oil circuit-breakers became necessary, apart from the stronger and stronger steel tanks which the designers used, for although the stronger tanks increased the pressure of the hydrogen, and therefore the interrupting ability, when a circuit-breaker

Fig. 5.—Sequence of stills showing arc extinction in an arc control structure.

did fail to interrupt, the resulting explosion was that much more severe.

The next step in the development of the oil circuit-breaker was the invention of arc control structures. These were constructions of synthetic resin board or similar material designed to retain the oil in the immediate region of the arc, so that a lot more oil was cracked into gas, and a much higher local pressure (which was not, however, transmitted to the tank) was produced round the arc. Even more important, the gas so formed was channelled as a blast through the arc, further increasing the ratio of W to K and thus still further shortening the time constant. Fig. 4 shows diagrammatically the action of such an arc control structure. As the moving contact rod is drawn downwards, the gas generated by the resulting arc has to flow across the arc stream to escape from the structure into the tank. Fig. 5 is a sequence of stills taken from a high-speed film showing the behaviour of the arc and the gas in a model arc control structure.

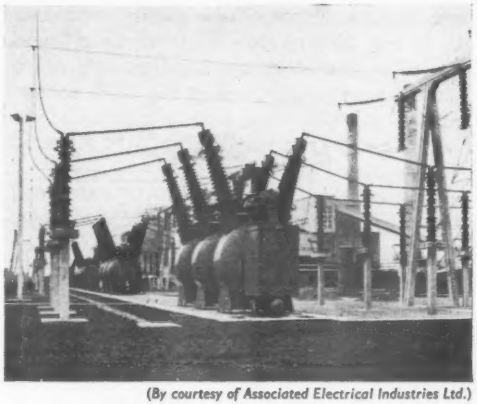
A large modern oil circuit-breaker is shown in Fig. 6. This circuit-breaker uses six arc control structures in series within each steel tank.

Once it was appreciated that a blast of gas was a good method of reducing the diameter of the arc and shortening its time constant, it was an obvious step to use air, and take it from a reservoir where it was stored at some suitably high pressure. Thus the air-blast circuit-breaker was born, and this type of breaker has the advantage that the pressure of the blast is under the control of the designer and does not depend on the arc itself. The air flow is most commonly along the axis of the arc, although other arrangements have been used. Fig. 7 shows the basic principles of an axial flow air-blast breaker. When in the closed position, current can flow between the rod-shaped moving contact and the nozzle which forms the other contact. To open the circuit-breaker, compressed air is allowed to flow into it, causing the moving contact to retract, and flowing out of the nozzle. An arc is drawn between the rod and the nozzle and is swept into the nozzle by the air blast, transferring from the back surface of the nozzle to the downstream probe which is electrically connected to it. At the current zero, the arc is extinguished as its resistance rises rapidly because of the powerful cooling and scouring action of the air blast. Pres-

sures up to about 400 p.s.i. are commonly used in these breakers, but the use of much higher pressures is being investigated in various laboratories.

Fig. 8 shows a series of stills taken from high-speed ciné film in which the various positions of the arc can be clearly seen. Fig. 9 shows a complete air-blast circuit-breaker in a switching station. The air reservoir is the long tubular base and the vertical porcelain columns are hollow, and serve to carry the air up to the interruptor heads, of which there are a number in series.

One fairly recent innovation is the use of electronegative gases in a closed cycle blast-type breaker. The gas that has been most used is sulphur hexafluoride, which has the merit of forming negative ions, which recombine with positive ions to form neutral atoms much more rapidly than do electrons.



(By courtesy of Associated Electrical Industries Ltd.)

Fig. 6.—7500 MVA oil circuit-breaker.

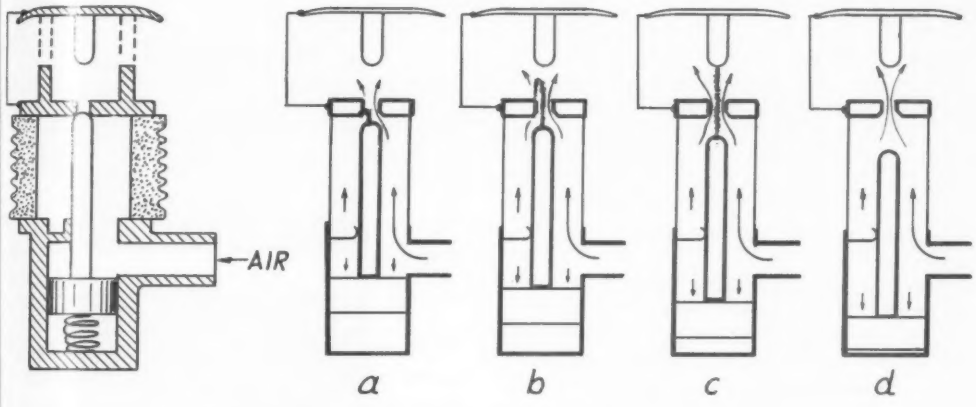


Fig. 7.—Principle of operation of axial flow air-blast circuit-breaker.

It also has a much higher electric strength, as well as other advantages. Large circuit-breakers using sulphur hexafluoride have very recently gone into service in the United States, and may appear in this country as well.

The oil and air-blast circuit-breakers which have so far been described are by far the most important types. Both of them depend on flowing gas to give arcs with short time constants. These two types are the only ones which are used at really high power levels.

A rather different circuit-breaker which is becoming widespread at lower voltages, up to 11 kV, is the arc chute circuit-breaker. This is almost a return to the old knife switch, except that the arc is no longer allowed to wander about, but is driven by a magnetic field into a porcelain labyrinth called an arc chute. There it is greatly lengthened and reduced in cross-section by being forced magnetically into narrow slots into porcelain plates. The high arc resistance required for arc extinction is built up over a period of a hundredth of a second or more rather than in a few tens of microseconds as in an oil or air-blast breaker. These arc chute circuit-breakers are often used in generating stations to control boiler feed pumps and similar

loads and contain no oil nor require compressed air. In Fig. 10 the successive positions of the arc as it is lengthened by the magnetic field can be seen diagrammatically, and in Fig. 11 is shown a sequence of stills taken from a high-speed ciné film. The very great lengthening of the arc which occurs is clearly visible.

There are many other types of switch and circuit-breaker but most of them are relatively unimportant compared with the three that have been described, and in any case, all of them could be fitted into one or other of the three categories. The only exception is the vacuum switch, which is most suited to switching small currents at high voltages. The arc in such a switch is very different from the high pressure arc and has a time constant measured in fractions of microseconds rather than microseconds. It is not yet economically important in this country.

Switchgear Testing

Since it is not yet possible to design switchgear from first principles, testing plays a larger part in this branch of electrical engineering than in many others. Not only must circuit-breakers be tested repeatedly, to verify the design, but the finished product must be rigorously tested for the various switching operations that it will have to perform in service.

The heart of a switchgear testing facility is a group of large alternators, specially designed to withstand repeated short circuits. These alternators, which when connected together can give a very high power output for short periods, feed the switchgear under test via inductances and/or transformers, through another circuit-breaker of proven interrupting ability, just in case the switch on test fails to interrupt the short-circuit. In the course of a test the performance of the circuit-breaker is recorded by oscillographs, cameras and other instruments.

Because of the very high capital cost of such testing plant, and the very large sizes of circuit-breaker now being manufactured, considerable effort is being applied to the development of methods of so-called 'synthetic' testing, in which the current which the breaker must interrupt is supplied at a low voltage from one source, and the voltage that appears across it immediately interruption is supplied from another. It is probably

Fig. 8.—Sequence of stills showing arc extinction in an axial flow air-blast circuit-breaker.

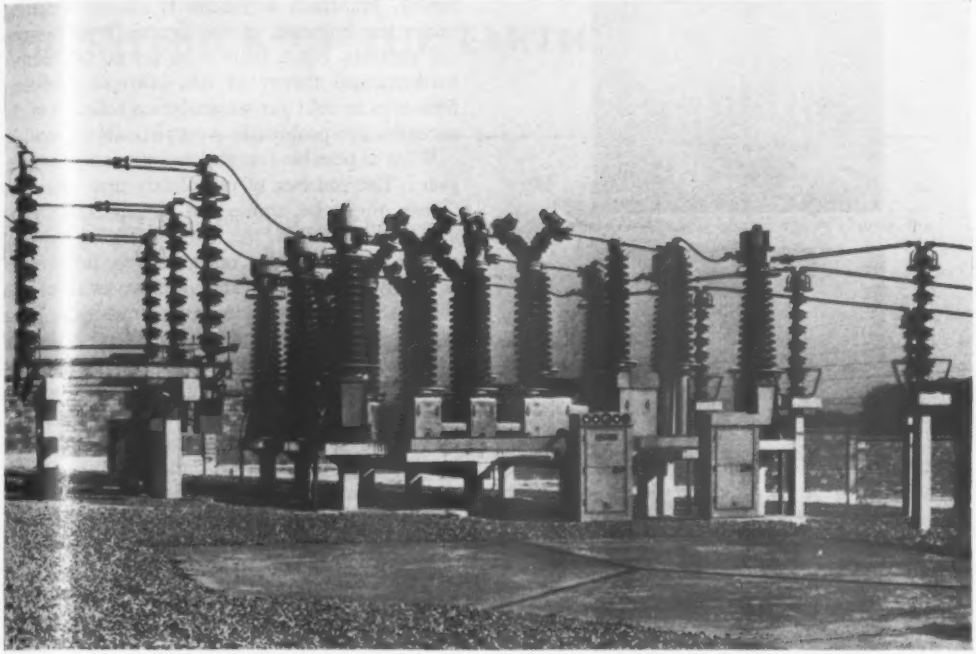


Fig. 9.—7500 MVA air-blast circuit-breaker. (*By courtesy of A. Reyrolle & Co. Ltd.*)

fair to say that in the not too far distant future all really large circuit-breakers will be tested 'synthetically'.

Research and Possible Future Developments

Research into the fundamentals of arc extinction has been in progress for many years, and it seems very unlikely that quantitative solutions will be found to the arc extinction problem except in an empirical form. The problem is extremely complex because in a circuit-breaker nozzle there is a hot (but not uniformly hot) turbulent and partially ionised gas flowing at the speed of sound. In this turbulent blast some ions and electrons are recom-

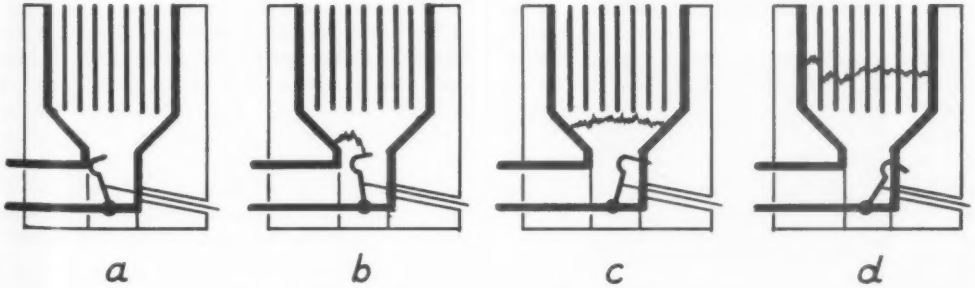


Fig. 10.—Principle of operation of arc chute circuit-breaker.

Fig. 11.—Sequence of stills showing arc extinction in an arc chute circuit-breaker.

bining, but fresh ionisation is always occurring under the influence of the electric field between the contacts. Since there is as yet no satisfactory mathematical theory of non-isotropic turbulent flow even in cold gas, an analytical solution of the arc extinction problem is as yet virtually impossible.

What of possible future developments in switchgear? The number of completely new principles which might be applied to circuit interruption seems very limited, but two interesting types of switch which are now being actively investigated in many laboratories are vacuum switches and solid state devices based on the transistor. These two types of switch, and more conventional types, using uncommon gases or liquids, seem to be the most likely roads which could lead to new types of switchgear.

Should developments in direct current power transmission call for large d.c. circuit-breakers, there are several ways of switching high-voltage direct current, and there seems to be little fundamental difficulty involved, although considerable development work will have to be done before such switches are commercially available.

Post-script

The ability to control the flow of power in our electrical transmission systems is fundamental to their satisfactory performance, and thus to our present industrialised society.

The necessary switches and circuit-breakers have been developed, from very crude beginnings, to their present sophisticated state almost without benefit of theory.

It is to be hoped that a quantitative theory of switchgear will one day be developed, but the day does not seem near at hand. Nevertheless, there is little danger that the development of switchgear will be unable to keep pace with the steadily increasing power levels of our electricity supply systems.

THE INTERIOR OF THE EARTH*

By Dr. R. STONELEY, F.R.S. *Department of Geodesy and Geophysics, University of Cambridge*

Man, by his muscular power alone, has not succeeded in digging far into the interior of the Earth—the Earth is tough, and there is a lot of it—and even the vast efforts of modern engineering have been confined to excavating and drilling to depths of less than ten miles. Thus, information about the deep interior must be obtained by indirect evidence and argument, some of it very indirect, and the geophysicist shares with the astronomer the handicap of not being able to sample at will the materials that he wishes to study. Sometimes the chain of argument is long and tenuous, and often the investigator seeking a precise numerical value must be content to find merely an order of magnitude.

The increase of temperature with depth in mine-shafts, as well as the existence of volcanoes, must long ago have led to the conjecture that the Earth is very hot inside—how hot we will discuss later. In ancient and medieval times the state of the interior was a matter about which speculations could be made freely, often in accordance with theological predilections. The step towards any reasonable idea of the internal structure had to await the formulation of quantitative laws of dynamics, physics and chemistry.

Up to about the end of the nineteenth century the information available concerning the structure and composition of the Earth's interior was of a general nature only, and was derived from a number of widely different scientific disciplines. The shape of the Earth was known from astronomical and geodetic measurements to be approximately an oblate spheroid, and the dimensions likewise were reasonably well determined. The usual process of geodetic triangulation available on land was not available across the oceans, but the classical researches of A. C. Clairaut on the theory of the figure of the Earth indicated the means whereby measures of gravity over the oceans could be used to supplement measurements on land, provided that a sufficiently stable platform could be devised for use at sea. Further, the variation of gravity along an arc of the meridian determines the polar flattening, and corroborates the method of direct geodetic measurements, which in effect uses the elevation of an ideal Pole Star at varying distances measured along a meridian. The mass of the Earth was known from the mean value of gravity as soon as the constant of gravitation had been determined in the laboratory by such experiments as those of C. V. Boys.

Some general idea of the distribution of density within the Earth could be inferred from astronomical data. The approximate constancy of the direction of the polar axis in space over a period of several years supported the idea that the distribution of matter must be very nearly symmetrical about this axis, regarded as the axis of figure. The arrangement of matter within the Earth determines the 'moments of inertia', which in angular motion occupy a rôle analogous to mass or 'inertia' in translatory notion; the moment of inertia about an axis is found by multiplying every element of mass by the square of its distance from the axis, and by summing all these contributions. For instance, the moment of inertia of a uniform solid sphere, of mass M and radius R, is $\frac{2}{5}MR^2$; for the Earth, supposed symmetrical about its polar axis, the moments of inertia are denoted by C about the polar axis and A about any diameter in the plane of the Equator. Now in relation to the plane of the Earth's orbit round the Sun (the

* Presidential Address delivered to Section A (Physics and Mathematics) on September 1, 1961, at the Norwich Meeting of the British Association.

'ecliptic'), the direction of the Earth's axis is not constant, but rotates in a conical path about the axis of the ecliptic—that is to say, the Earth's axis does not continue to point to the same point of the heavens (somewhere near the Pole Star) but describes in the sky a circle of angular radius about 23° in a period of about 26,000 years. This 'precession of the Equinoxes' is ascribable to the attraction of the Sun and Moon on the equatorial bulge of the Earth, and depends on the ratio $C/(C-A)$, which may thus be calculated, and is about 305. Now according to a celebrated theorem of Clairaut the ellipticity of the Earth ϵ (defined as $(c-a)/c$, where a, c are respectively the equatorial and polar radii), the moments of inertia, and the ratio m of the centrifugal force at the equator to mean gravity, are connected by the relation

$$3(C-A)/MR^2 = 2\epsilon - m$$

Using the values $m = 1/288$, $\epsilon = 1/297$, and the above value of $C/(C-A)$, it follows that $C = 0{\cdot}33MR^2$; in comparison with the value $0{\cdot}4MR^2$ for a uniform sphere, this indicates that the Earth is centrally condensed. It might be expected of course that to some extent the Earth would condense centrally under its own gravitational attraction, but computation shows that with any materials of which the compressibilities are known from laboratory experiments the condensation from this cause would be insufficient to give the required value of C. This result is very important, since any proposed distribution of density in the Earth must satisfy the requirement $C = 0{\cdot}33MR^2$.

There is another piece of astronomical evidence that throws some light on the rigidity of the Earth as a whole. Suppose we consider a rigid body, with an axis of circular symmetry passing through the mass centre, and confine our attention to the angular motion, which may be treated separately from the motion of the mass centre. Initially the body is supposed rotating about this polar axis, which in the absence of outside couples will maintain the same direction in space; if a small spin is given to the body about an axis at right angles to the polar axis the instantaneous axis of rotation will describe a cone in the body, (the polhode cone) and likewise a cone in space (the herpolhode cone). Now observations of the altitude of stars are regularly made to determine the direction of the polar axis of the Earth: in reality they determine the direction of the instantaneous axis. Thus, in the case considered the apparent North Pole will describe on the Earth's surface a circle about the mean position; this phenomenon is the 'Eulerian Nutation' and would give a periodic change of the latitude of any place in a period of $A/(C-A)$ days (or, near enough, $C/(C-A)$ days). Such a change in 305 days was looked for, and not found. Actually in 1891 a small motion of the North Pole was detected by S. C. Chandler which was less regular in appearance and corresponded to the superposition of a small annual motion and a small roughly circular movement in a period of about 428 days. The cause of the free period of 428 days was soon suggested by S. Newcomb; the lengthening is to be expected if the Earth is not perfectly rigid, and, indeed computation shows that such a lengthening is consistent with the assumption of an overall rigidity of the order of that of steel. It happens that the yielding of the Earth to the tidal forces exerted by the Moon and Sun (the 'Earth Tide') is in general agreement with this result.

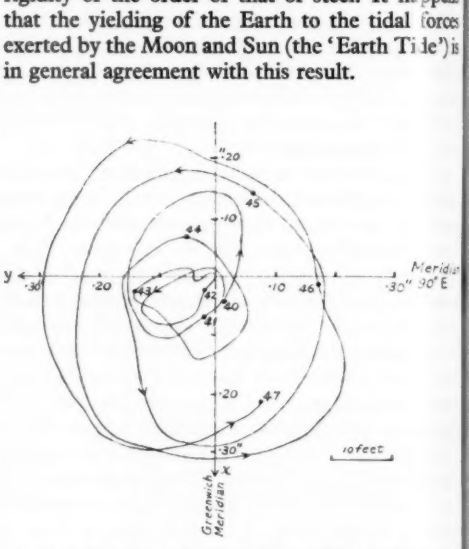


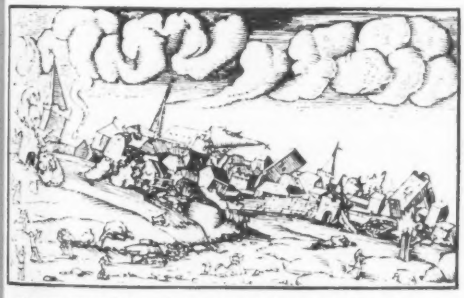
Fig. 1.—Variation of Latitude from 1940 to 1947 (after L. Carnera).

The idea that the Earth is so rigid was in contradiction to much older ideas that the interior must be fluid. Such an idea no doubt originated from the existence of volcanoes and from the observed increase of temperature with depth in

mines. The possibility of a very thin crust over a molten interior was disproved by Lord Kelvin's observation that in these circumstances the ocean floor would rise and fall with the changes in the tide-raising forces, so that ocean-tides would not be observed.

The foregoing description of the information available at the beginning of this century throws into relief the great advances made in the past half-century in our detailed knowledge of the structure and composition of the Earth's interior, meagre though this still appears to geophysicists. This great development has been made possible by many lines of research, but particularly by the study of earthquakes. Even if earthquakes did not occur, we could now obtain much of this information from the records of large nuclear explosions.

Historical records of earthquakes have been made from early times, and instrumental observations were made as far back as the second century A.D. in China. More sensitive recorders of the shaking of the Earth's surface were devised during the nineteenth century and large earthquakes were detected at great distances from their apparent place of origin. As will be seen from the illustration of an earthquake record (seismogram) the confusion of oscillations needs patience and experience, as well as the intercomparison of a number of seismograms from different stations and of different earthquakes, in order to pick out consistent features.



Wirkungen eines Erdbebens. Nach einem Holzschnitte in Sebastian Münsters

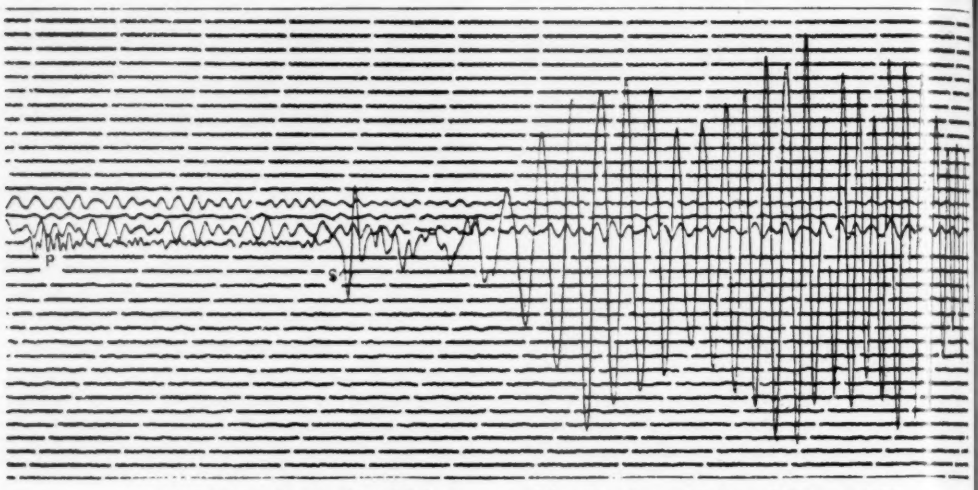
Fig. 2.—Medieval wood-cut of earthquake damage.

Confining our attention for the moment to shocks recorded at angular distances from about 25° to 100° it is seen that the record starts with a distinct kick, known as *P*. There is a prominent kick arriving some time later which is called *S*. Now it is found that the interval $S-P$ depends, as a first approximation, only on the distance from the earthquake (the 'epicentre') to the station; *P* is evidently outrunning *S*, and from the interval $S-P$ this 'epicentral distance' can be estimated; in this way travel times of *P* and *S* are tabulated when the instant of the commencement of the shock is known from local observations. The interpretation was first given in 1899 by the geologist R. D. Oldham. It was proved by S. D. Poisson in 1829 that two kinds of elastic waves can be propagated through the interior of an elastic solid, the compressional wave, in effect a sound wave, and a distortional wave, depending only on the rigidity, in which the displacement of the particles of the solid is at right angles to the direction of propagation. Further, by the numerical analysis of the tables of travel times the paths of the rays and the velocities of propagation at all the depths reached can be ascertained. The directions of movement in *P* and *S* support the interpretation that *P* is a compressional wave and *S* a distortional wave.

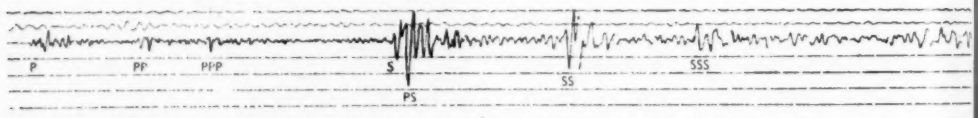
Some important information thus emerges. Leaving aside small corrections for ellipticity it follows that the Earth must be spherically symmetrical. Further, the Earth must be solid down to about half-way to the centre. If the density ρ is known, the velocities α and β of the pulses *P* and *S* give the elastic constants λ, μ according to the formulae $\alpha^2 = (\lambda + 2\mu)/\rho$; $\beta^2 = \mu/\rho$.

This is the general picture as given by waves that have travelled an epicentral distance not greater than about 108°. From that distance, however, the records show different features from what is seen at shorter ranges. The initial pulse *P* is of small amplitude and *S* seems to die out altogether. At an angular distance of 142° a very prominent initial onset occurs instead of *P*, and this is identifiable right round to the antipodes. Oldham's explanation put forward in 1906, and borne out later by the researches of B. Gutenberg, was that in the deep interior of the Earth (actually at a depth 0·455 R.) the solid shell (nowadays called the 'mantle') gives place to a 'core' that is fluid, in the sense that it does not transmit distortional waves. The velocity of compressional waves suffers a sharp drop in passing from mantle to core, so that there is strong refraction at the

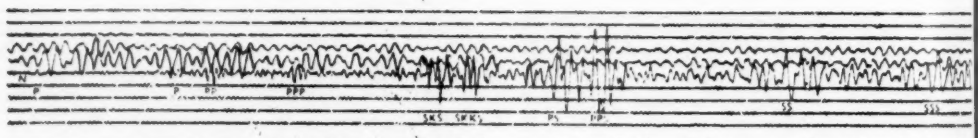
junction: thus a ray, originating near the Earth's surface and dipping a little more steeply than one that just emerges at 108°, is refracted through the core so as to emerge near the antipodes, and, in fact, all rays leaving their origin (the 'focus') more steeply than this critical ray will emerge at 142° or beyond, so that 142° constitutes a distance of minimum deviation, as with the caustic seen in a teacup when the Sun is shining into it—hence the large amplitudes at about 142°. This ray through the core is denoted by *PKP*. A confirmation that the transition from mantle to core is sharp was provided by the discovery by V. Conrad of waves (*PcP*) reflected at the surface of the core. From the travel times of *PKP* the distribution of wave-velocity with depth was worked out by H. Jeffreys, B. Gutenberg and others.



The earthquake of 23rd July 1929 recorded at Copenhagen at epicentral distance 18·6°.



The earthquake of 30th June 1936 east of Kamchatka recorded at Copenhagen at epicentral distance 70·1°.



The earthquake of 1st March 1948 off the west coast of New Guinea recorded at Scoresby-Sund at epicentral distance 108°.

Fig. 3.—Typical seismograms (after Gutenberg).

The existence of *P* waves emerging between 108° and 142° was for a long time thought to be the result of diffraction, but it was suggested in 1936 by Miss I. Lehmann that they might originate through the refraction of steeply-dipping rays by an 'inner core'. This view has been generally accepted, following the demonstration by Jeffreys that the amplitudes of diffracted waves should be inappreciable at the angular distances, much less

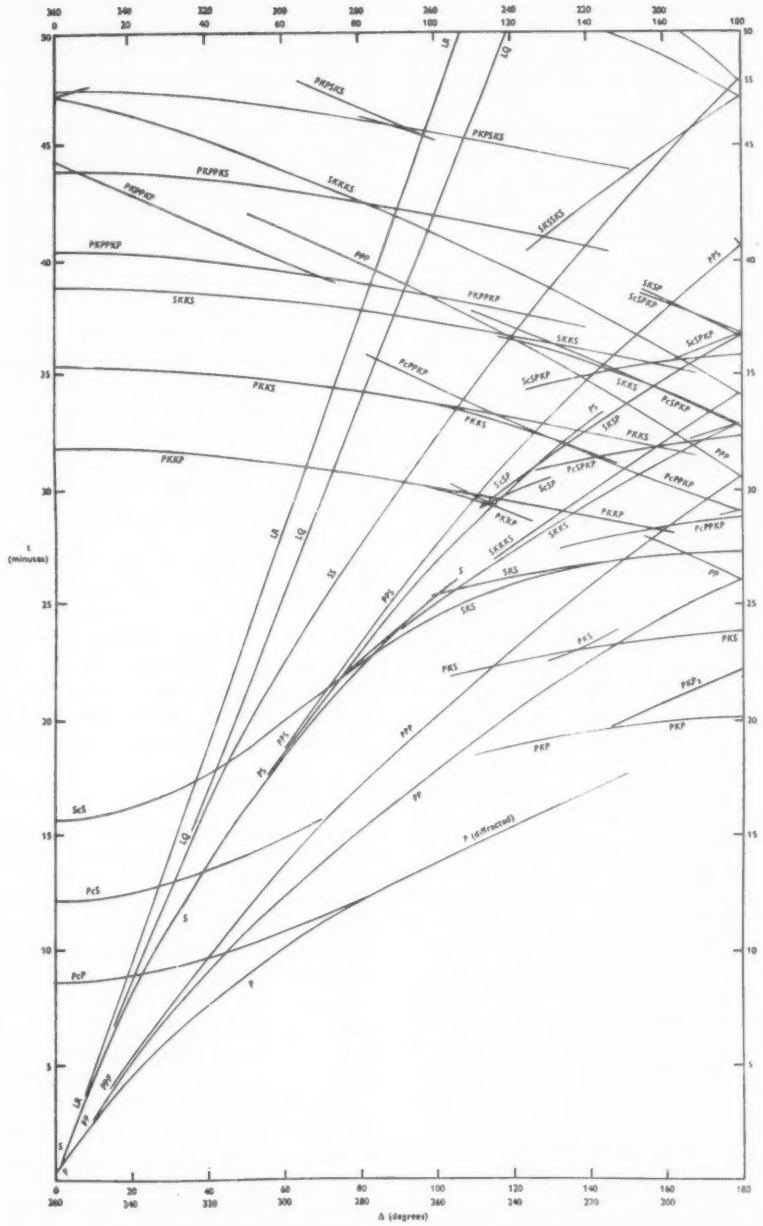


Fig. 4.—Earthquake travel times for a surface focus (after Jeffreys).

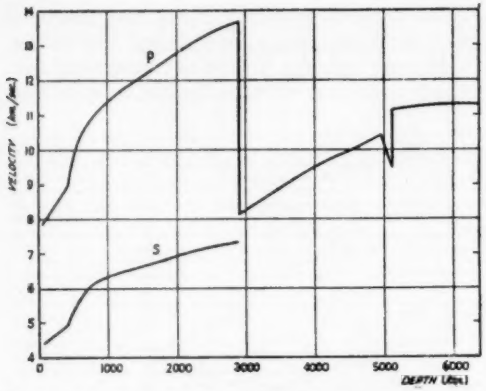


Fig. 5.—Velocities of P and S in the Earth's interior (after Bullen).

than 142°, at which they had formerly been classified as 'diffracted'. The radius of the inner core has been computed by Jeffreys, and by Gutenberg and Richter, as about 0·2 R.; whether the inner core is solid or fluid has not been finally settled.

So far little has been said about the distribution of density in the Earth. As mentioned above, the mean density is known from the radius, the surface value of gravity and the constant of gravitation: it is about 5·517 gm. per cu. cm. The distribution must give a moment of inertia about $0{\cdot}33MR^2$. It is reasonable to suppose that a distribution in which at any stage the density decreased downwards would be gravitationally unstable. In early discussions of the figure of the Earth 'laws' such as those of Laplace and Roche were proposed rather on the basis of analytic convenience than on detailed geophysical evidence. The hypothesis of E. Wiechert (1897) of a core of density 8·2 gm./cm³ and radius 0·78 R. with a rocky shell of density 3·2 gm./cm³ proved to be a good starting point for later investigations, and it was shown in 1926 by Jeffreys that by considering the effect of compressibility the seismic and astronomical data could be satisfied by identifying the Wiechert core with the Oldham–Gutenberg core.

The way to a more direct calculation of the march of density with depth was opened by an investigation by L. H. Adams and E. D. Williamson in 1923. If the p is the pressure in the Earth at a place where the density is ρ and the distance from the centre is r, then, if the Earth is in hydrostatic equilibrium, $dp/dr = -\rho GM'/r^2$, where G is the constant of gravitation and M' is the mass within a concentric sphere of radius r. The bulk modulus, defined as $\rho dp/d\rho$, is likewise $\rho(\alpha^2 - \frac{4}{3}\beta^2)$, so that if the chemical composition does not change $d\rho/dr = -G\rho M'/r^2(\alpha^2 - \frac{4}{3}\beta^2)$, and also $dM'/dr = 4\pi\rho r^2$. These two equations may be integrated step by step from the surface inwards, using the reasonable value $\rho = 3{\cdot}32$ gm./cm³ for the density at the top of the mantle and just below the continental layers, and taking account of the moment of inertia criterion.

This integration was carried out by K. E. Bullen in 1936 in an investigation of fundamental importance. Bullen found that a direct application of the above equations to the mantle as a whole, ignoring possible changes of constitution, led to an impossibly high value for the moment of inertia of the core. Now one such change had already been inferred from seismological evidence by P. Byerly, I. Lehmann and H. Jeffreys; at a depth of about 400 km., corresponding to a distance 0·94 R. from the centre, the rays travelling an epicentral distance of about 20° appear just to reach a level at which the velocity of P fairly suddenly undergoes a sharp rate of increase. Whether this '20° discontinuity' is a true discontinuity is a question that has not yet been settled. Below this level the rate of increase of velocity with depth falls off steadily

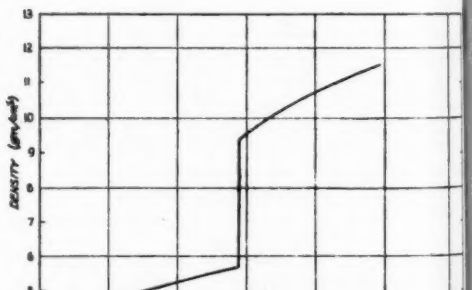


Fig. 6.—Variation of density in the Earth's interior (after Bullen).

down to a depth of about 1000 km., below which the rate of increase with depth is sensibly constant until the core is reached. There is some uncertainty regarding the density of the inner core, but by considering two extreme hypotheses Bullen was able to set reasonable limits to the possible distribution of density. With this knowledge, the elastic constants and the pressure, variation may be found directly. The question of the chemical composition will be discussed later.

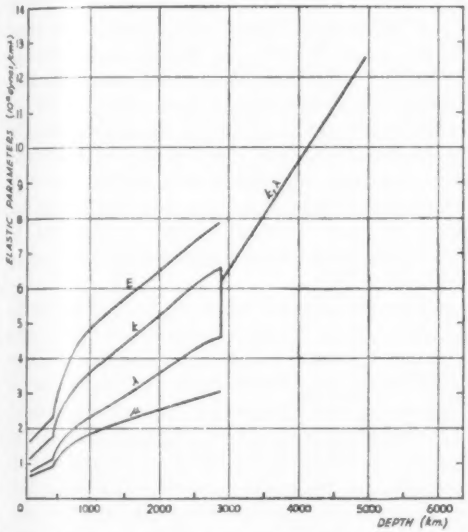


Fig. 7.—Variation of Young's modulus (E), bulk modulus (k) and Lamé's parameters (λ, μ) in the Earth's interior (after Bullen).

Now the layers of the Earth that are accessible by direct geological observation throw little light on the constitution outlined above (which is admittedly an over-simplification). The sedimentary rocks of the continents and ocean floors have been deposited, and often redeposited, since the time that the ancient granitic shields came into being. The time scale of the rocks is fairly precisely known from measurements of radioactivity, but the enormous contortions that the accessible parts of the coast have undergone prevent any belief that we have really typical specimens of the material of the mantle. Volcanic activity is local, and seems to be relatively superficial, and in view of the likelihood of magmatic differentiation it is risky to infer that plutonic rocks, particularly in their radioactive content, are typical of anything except the uppermost part of the mantle.

Here, however, seismology comes to our aid. Where an earthquake is recorded at a number of stations within, say, 1000 km. of the epicentre (the point of the Earth's surface above the focus of the shock), the time–distance curves, which are very nearly straight lines, give the velocities of compressional and distortional waves in the separate layers of the continent, as well as estimates of the thicknesses of the layers and the depth of focus. In this way it is inferred that the continents are about 35 km. thick, mainly granitic in general composition, with a layer of basic rock beneath in some regions, though whether this basic layer occurs in all regions is not settled. At the base of these continental layers is the Mohorovičić discontinuity, or M-discontinuity, below which is the general material of the mantle, consisting, it is thought, of ultrabasic rocks. This discontinuity appears to be world-wide. The submarine layers can be diagnosed by means of artificial explosions, either in the ocean or on the sea-floor; a similar method is employed in prospecting on land for oil or minerals, where the sub-surface structure is delineated by the records of explosions at a chain or 'spread' of portable seismographs. The constitution of the oceanic regions is by no means uniform: a typical region might consist of 5 km. of sea-water, with about 1 km. of sediments, increasingly consolidated with depth, below which is some 5 km. of basic rock extending to the M-discontinuity. All this, of course, is an over-simplification, especially as measurements of gravity indicate that on the whole the surface features are 'compensated', so that, for instance, underneath the mountain ranges is material lighter than the material of the mantle, and that, in consequence, the mountains have 'roots' extending far into the ultra basic material. The oceans are mainly compensated, and the M-discontinuity there is much nearer sea-level than on land.

Much additional evidence is forthcoming from the time of travel of the elastic surface-waves which form the most prominent feature of a seismogram after the arrival of S. They are of two kinds, Rayleigh waves, named after their discoverer, the 3rd Lord Rayleigh, and Love waves, discovered by

A. E. H. Love. They are distinguished by the direction of motion of the elements of the solid, which in Rayleigh waves has a vertical component and a horizontal component in the direction of propagation, while in Love waves it is horizontal and at right angles to the direction of propagation. The motion is more conspicuous near the surface of the Earth, and dies away with depth; the special interest is that the motion is dispersive, i.e. the wave velocity depends on the period, so that the record exhibits a long train of waves of slowly varying period: each constituent period travels with its appropriate group velocity. By assuming various likely models of the layering a comparison may be made of the calculated and observed dispersion curves; in this way, for instance, the difference between continental and oceanic regions can be clearly brought out. It should be emphasised that the identification of materials inferred from seismological evidence with actual rock types involves an assessment of probabilities. Thus the material just below the *M*-discontinuity has a compressional wave velocity of about 8·1 km./sec., and the consistency of the law of variation of density with depth supports the value of about 3·3 gm./cm³ for the density; but this does not identify the material chemically, and the evidence for thinking the material to be of the composition of an ultrabasic rock is that laboratory measures of the density and elasticity of olivine (a mixture of magnesium and iron orthosilicates in varying proportions) are consistent with the seismologically determined values for this region.

An interesting point arises in connection with the attempted identification of the materials within the Earth. Jeffreys calculated the depth of the 20° discontinuity to be 480 km.; the procedure already outlined then indicated a density jump there from 3·69 to 4·23 gm./cm³. The latter figure corresponds to a density at atmospheric pressure of 3·6 gm./cm³, which does not correspond to any material likely to be found in world-wide abundance at that depth. J. D. Bernal, whose attention was called to the possibility by H. Jeffreys, suggested that this jump might correspond to a change under pressure from a rhombic to a cubic form. Although this suggestion has not met with general agreement there is some experimental evidence that a change of the right order of magnitude should occur at the prevailing pressure.

A further development along these lines was proposed by W. H. Ramsey in 1948. He suggested that, under the high pressures obtaining within the region of the core, the olivine of the mantle might lose some of its electrons and become a high pressure modification, effectively a metal. It is a familiar fact that some substances, such as tin, can occur in a non-metallic or a metallic form according to the temperature and pressure. It has also been suggested that the surface layers originate in this manner: these changes would be reversible, and it is to be hoped that one day deep drilling down to the *M* layer, as in 'Operation Mohole', may clear up this point. Ramsey has applied the theory for hydrogen to the outer planets, and concludes that Jupiter and Saturn should consist of some 80 per cent of hydrogen. It should be mentioned that the usual identification of the core as iron had been based on the computed density and on the wide occurrence of iron in meteorites, as well as in the Sun. Ramsey's theory could be invoked to explain the inner core as a further stage of pressure degeneracy.

The question arises whether the material of the Earth has finite 'strength', that is, whether it can permanently resist deforming stresses, or whether it ultimately flows under small shearing stresses if these are operative over very long periods of time. The fact that the main overall spheroidal figure of the Earth closely approximates to a gravitational equipotential has led to the view that the Earth as a whole is in hydrostatic equilibrium. It was, however, pointed out by J. Barrell in 1914 that observations of the deflexion of the vertical indicate that the surface blocks are not supported purely hydrostatically as they would be if a little below the continents there were a layer of no appreciable strength, but that the weak layer, which Barrell called the 'asthenosphere', had a strength of about one-sixth of that of the surface rocks, an estimate which Jeffreys considers should be increased to about one-third. Some assumptions have to be made about the distribution of strength, regarded as the greatest stress-difference the material can permanently withstand without flow or fracture. If the absence of earthquake foci at depths greater than 0·1 R. is taken to indicate the absence of strength below that level, then to support typical surface features requires stress-differences reaching $3 \cdot 3 \times 10^8$ dynes/cm² at depths from 50

km. to 600 km.; these values are diminished if we assume the existence of strength right down to the boundary of the core. It should be mentioned that observations of the orbits of artificial satellites give a value of the ellipticity of the Earth's surface inconsistent with the hypothesis that the interior is in hydrostatic equilibrium.

Compared with the wealth of information obtainable from a study of earthquakes and large explosions, the knowledge derived from other lines of investigation is surprisingly scanty. Measurements of gravity have been made in great numbers all over the continents and the oceans, but their interpretation is not unique: according to a general theorem in the theory of gravitational potential an infinite number of subterranean mass-distributions will account for a set of values of gravity observed over a large area, so that additional assumptions must be made about the mass-distribution, and at present no certain inference can be drawn in this way about the distribution, particularly at great depths.

The mean temperature of the surface is determined by the balance between the heat received from the Sun and that radiated out into space; it appears to have had much the same value throughout the time since the oldest sedimentary rocks were deposited. Thus the region near the Earth's surface is sensibly steady. Determinations of temperature in borings have been made in many parts of the world, including the ocean floors: the rate of outflow of heat is given by the product of the temperature gradient and the thermal conductivity where the latter is known. It was verified by Sir Edward Bullard some years ago that this rate of outflow was the same throughout one of the boreholes in South Africa. It turns out that the rate of outflow is much the same in all parts of the world, namely $1{\cdot}2 \times 10^{-6}$ cal. per sq. cm. per sec. Now it is most unlikely that this rate of outflow could be accounted for by a store of primitive heat, supplemented by that liberated from the transformation of gravitational potential energy during contraction.

It is nowadays believed that much of the heat-flow is maintained by the heat liberated during

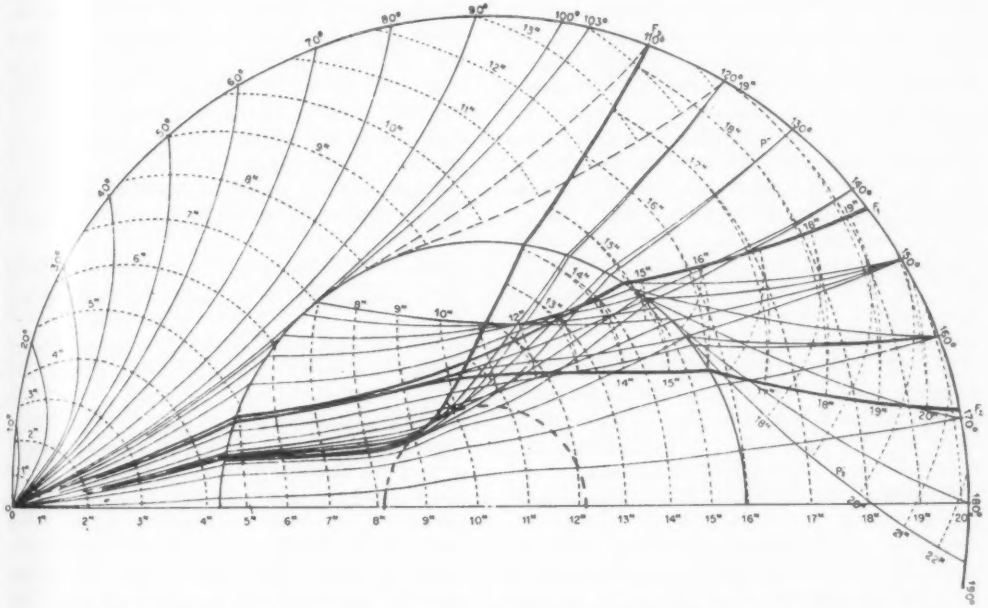


Fig. 8.—Wave paths and wave fronts of direct compressional waves in the Earth (after Gutenberg).

radioactive transformations. Much work has been done along these lines, some of it a matter of contention, but roughly it may be said that the radioactivity of granites (as determined from specimens obtained from the Earth's surface rocks), together with a rather uncertain amount in more basic rocks, will account for a heat outflow of about the right order of magnitude. Unfortunately the heat outflow does not determine the distribution of temperature throughout the interior. A problem in heat-flow can be made definite if one can specify the temperature distribution at some initial instant, together with the heat sources at all times, but for the Earth some hypothesis, such as solidification of the mantle through cooling of a molten magma, must be set up so as to specify the precise problem. Thus the discussion soon begins to involve cosmology, with such complications as the effect of the variation with time of the 'constant' of gravitation. At the present time there are many advocates of the idea that the Earth is expanding, rather than contracting as formerly believed, and despite many detailed discussions, such as that of L. Egyed, it is premature to attempt to sum up the evidence.

In modern times the Earth's magnetic field has been the subject of much research. A harmonic analysis by C. F. Gauss in 1836 of observations made over the surface of the globe showed that the main part of the magnetic field is what is nowadays called a 'dipole field', that is, it is equivalent at points on or outside the Earth to the field of a magnet of small dimensions situated near the middle of the Earth, or alternatively, to the field of a uniformly magnetised sphere. This analysis further decides whether a given term in the expansion is attributable to sources inside the Earth or from outside.

The origin and maintenance of the dipole field afford a problem not yet finally solved. An immediate difficulty arises if the Earth is supposed to be permanently magnetised; the temperature reaches the Curie point for iron at about 750° C., so that it is unlikely that magnetism can be retained in ferromagnetic substances except in a thin surface shell. It is improbable that such a shell could become so intensely magnetised as the value of the Earth's field requires. To explain the dipole field by electric currents circulating in the interior involves a large current flow for which there is no obvious origin: if such a current exists as a remnant of a decaying current set up long ago, the known order of the rate of decay of the current indicates a primitive current of enormous strength, the origin of which is inconceivable in our present state of knowledge. Various other suggested causes, such as the gyro-magnetic effect, have been suggested, but are either very improbable or else give an effect of far too small a magnitude. There remains for consideration the development of a suggestion, first put forward by Sir Joseph Larmor in 1919, that the Earth acts as a self-exciting dynamo. An investigation by T. G. Cowling in 1934 showed this to be impossible for an axisymmetrical magnetic field, but later work by Sir Edward Bullard and by A. Herzenberg has shown that in certain circumstances the existence of a self-exciting dynamo is possible; however, a model that will account for the Earth's dipole field has yet to be worked out in full detail.

It has long been known that the direction of the Earth's field at any place is slowly changing, and you will have noticed this variation of the direction of the magnetic north recorded on the margins of maps. Between 1580 and 1820, for instance, this direction varied at London, England, from 11° E. to 24° W. These 'secular changes' are found to be regional and by removing the steady mean field it is seen that the secular variation groups itself into about a dozen regions, the pattern of each region having a general westward drift at a rate of one circuit of the Earth in a period of the order of a thousand years. This phenomenon has evoked much discussion in recent times, and the theory has been put forward by Bullard and others that the material of the core is subject to a movement like that of a small number of large vortices circulating in a general westward direction.

Superposed on these slow changes are fluctuations such as the solar daily variation and the lunar semi-diurnal variation. In addition there are the 'storm-time variations' attributable to sudden irregular changes in the Sun's activity. Sir Arthur Schuster in 1889 separated the solar daily variations into parts that originated inside and outside the Earth and applied H. Lamb's theory to prove that the internal part was ascribable to currents of electricity induced in the Earth by the external part of the field. In 1919 S. Chapman analysed the

solar and lunar daily variations in detail and showed that their internal fields were consistent with a conducting 'core' surrounded by non-conducting material some 250 km. thick; A. T. Price and S. Chapman extended this work to include the storm-time variations. Using laws of special types B. N. Lahiri and A. T. Price found that both the daily and the storm time variations require a great increase of electrical conductivity below 250 km., the rapid rise being in the neighbourhood of 700 km. Chapman has pointed out that longer period oscillations, with induced currents penetrating to greater depths, should yield more precise information. The better coverage of magnetic stations in modern times should add to the precision. It is noteworthy that the density distribution, the existence of the '20° discontinuity' and magnetic observations all point to a change in the properties of the Earth at a depth of the order of 400 km.

There is space only to mention some of the other items of information that refer to the properties of the interior of the Earth. The internal viscosity must not be so low as to contradict the observations of Earth tides: estimates from the observed uplift of Fennoscandia have given a value some 10^{13} times that of pitch, but the facts as a whole appear to be widely inconsistent. The passage of longitudinal elastic waves through the Earth's core indicates that the viscosity of the core is not greater than 10^{8} C.G.S. units. The discussion of the variation of latitude by Jeffreys showed that the amplitude is reduced by a factor $1/e$ [$= 0{\cdot}368$] in about 15 years: this damping might conceivably arise from tidal friction in seas, from imperfections of elasticity in the shell, or from viscosity in the core, but Jeffreys has shown that, of these three, only the second is likely, and if this is the cause, then the damping of seismic waves in the mantle is to be attributed to scattering and not to imperfections of elasticity.

To sum up, the dynamical and seismological data lead to a consistent and detailed picture of the

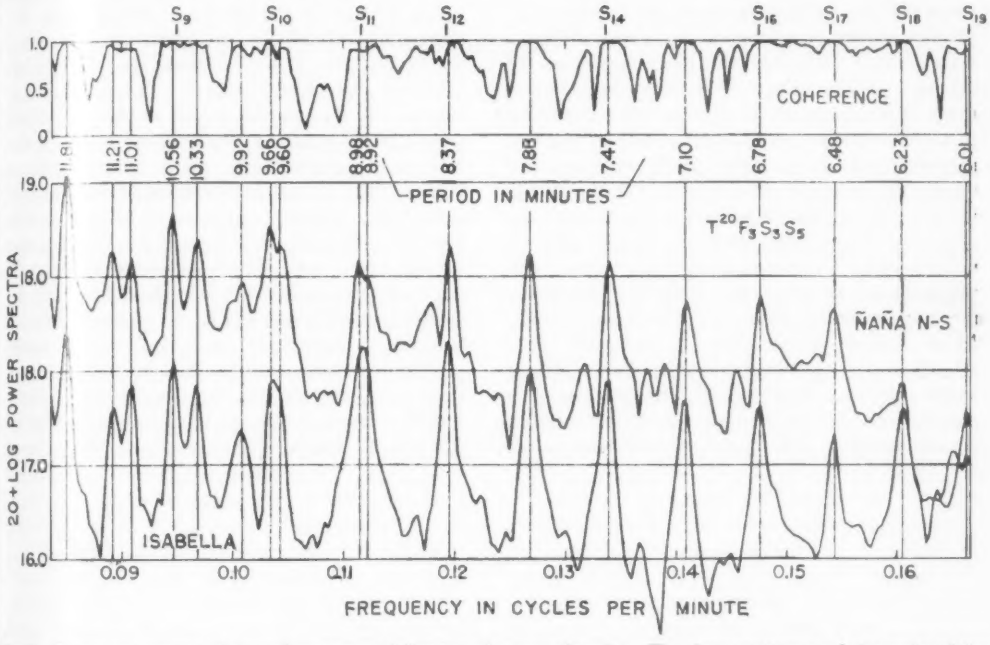


Fig. 9.—Frequency spectra of ground movement following a large earthquake. The close agreement of the peaks of the spectra with the calculated frequencies of the free oscillations (marked S_9 to S_{19}) is noteworthy (after Benioff, Press and Smith).

distribution of elasticity and density within the Earth. Other mechanical properties, such as viscosity and strength, are known only vaguely. Despite the large amount of work already done in geomagnetism the information forthcoming is not detailed, but links up with seismological data in indicating a rapid change of properties at a depth of some 500 km. In view of the electric conductivity of the mantle, exploration by electromagnetic waves is not practicable. One overall check on the accuracy of the values of elasticity and density must be mentioned in concluding. The knowledge of these constants permits calculation of the free periods of oscillation of the Earth: there are two types, the torsional modes and the dilatational modes. The calculation of the periods of the series of modes is heavy, but has recently been effected, notably by C. L. Pekeris and his co-workers, with the help of an electronic computer. Regularly periodic forces, like the tidal forces of the Sun and Moon, would not be expected to set up these vibrations, but they might well be generated by a sudden release of energy, as in an explosion or an earthquake. Last year a concerted attack was made on this problem: the seismograms, including the Chile shocks of May 1960, for periods of time as long as 260 hours following an earthquake (which itself ordinarily subsides within a few hours) were put through a numerical process which in effect records a frequency spectrum. The result of this research of H. Benioff, F. Press and S. Smith is most striking: the free periods of oscillation show up as sharp peaks, agreeing closely with the predictions of Pekeris. At about the same time L. B. Slichter, J. C. Harrison and N. F. Ness similarly analysed the records of a specially sensitive gravity recorder in respect of the same Chile earthquakes; again, a sequence of peaks in the frequency spectrum corresponds to the predicted values, except that the gravimeter should not record the torsional modes—and in fact it does not! An analysis by B. P. Bogert of the long-period records of the great Chile earthquake of May 22, 1960, likewise showed clearly these free periods. Finally, the analysis by B. A. Bolt of a set of records of earth tides recorded by horizontal pendulums again reveals a long sequence of torsional modes. The close agreement of these really beautiful researches completely confirms the details of Bullen's picture of the interior of the Earth.

CHEMISTRY AND THE SPECTROSCOPE*

By Prof. R. G. W. NORRISH, F.R.S. *Department of Physical Chemistry, University of Cambridge*

In 1859 the spectroscope was invented by Bunsen and Kirchoff. They built an instrument destined to reveal the forms of the cosmos, the infinitely great and infinitely small. By its aid the mystery of the expanding universe, the anatomy of the stars and the intimate structure and behaviour of the atom are unfolding before us; and within these limits there is no field of chemistry in which the spectroscope has not been paramount: the analysis of matter by the discovery of new elements, the elucidation of molecular structure, the understanding of valency, and the study of the detailed mechanism of chemical reactions. The spectroscope has become the most powerful of all instruments of scientific research.

Practically all the components were available when Kirchoff came to Heidelberg in 1854—the diffraction grating, the prism and the lens—but the basic idea of using the prism for chemical analysis was due to Bunsen. About one hundred years earlier Marggraf had drawn attention to the use of flame colouration for distinguishing soda and potash and possibly with this in mind, Bunsen had applied himself, with the use of a prism, to analysis of light emitted from metallic salts heated in the bunsen flame. This light is composed in general of a few monochromatic emissions characteristic of each metal and, passed through the prism, gives corresponding coloured images of the flame. Bunsen found the best resolution by using narrow flames and it was a short step when Kirschoff joined him to use a slit and a lens to present parallel light to the prism, and a telescope to view the images of the slit in focus. So was born the first spectroscope and with this simple device Bunsen early pointed the way to spectroscopic analysis by discovering rubidium and caesium. Kirchoff at the same time was able to establish the principle that a metallic vapour can reabsorb its characteristic emission and so to account for the dark Fraunhofer lines in the spectrum of the sun by the presence of certain elements as gases in its atmosphere. Thus the spectroscope very soon became of importance to the astronomer, with the result that many terrestrial elements were shown to be present in the sun and stars, and helium was discovered in the sun by Lockyer before it was found on earth.

The use of quartz instead of glass and a fluorescent plate detector by Stokes made possible the viewing of spectral lines in the ultra-violet as far as 1830 Å, and this great step forward was sealed by the application of photography to the permanent recording of spectra. Simultaneously the development of the use of the grating by Cornu and Rowlands led to the characterisation by Angström of spectral lines by their absolute wavelengths, and yielded those quantitative developments of spectroscopy that have made it the fundamental rock upon which the philosophy of the physicist and astrophysicist is built.

The extension of the visible spectrum of Newton was first made in 1800–1 when Ritter detected light beyond the violet by its action in blackening silver chloride, and Herschel observed infra-red radiation beyond the red by means of a sensitive thermometer. Thus when the spectroscope took shape the study of the spectrum became possible in both directions—by using quartz optics and photographic recording for the ultra-violet, and prisms of rock salt sylvine or fluorite with concave mirrors and radiometric recording for the infra-red.

* Presidential Address delivered to Section B (Chemistry) on August 31, 1961, at the Norwich Meeting of the British Association.

The limit to observation set at 1900 Å by the opacity of quartz and by the absorption of light by the oxygen of the air was overcome by the invention by Schumann of the vacuum spectrograph which enabled Lyman and others to extend observations in the ultra-violet as far as 500 Å. The vacuum spectrograph involves the use of fluorite transparencies, a concave grating operated in vacuo and gelatin-free photographic plates.

Beyond this region in the domain of X-rays the X-ray spectroscope of von Laue and the Braggs has made possible the elucidation and measurement of crystal structure. In the hands of Moseley it led to the discovery of atomic numbers and gave form and meaning to the periodic classification of the elements.

Thus there has been revealed a vast range of frequencies of electromagnetic vibrations of great significance to the chemist, and to it has been added in recent years the discovery of micro-wave spectra and their application to the study of molecular structure by nuclear magnetic resonance and electron spin resonance.

I hope I may be forgiven for presenting this brief and I fear inadequate historical recapitulation with which I know very many of you are familiar. I put it forward in order to emphasise a milestone in scientific history—the century of the spectroscope.

This paper is intended to give an account of a new and powerful method by which the intimate nature of photochemical and thermal reactions can be studied and which yields objective information about the free radicals and other transient intermediates taking part. These intermediates generally have very short lives, measured in millionths of a second; nevertheless it has been possible to photograph their characteristic spectra at successive intervals of time and so to measure the rates of their growth and decay during chemical reaction. Sometimes they are produced in a highly energised state of thermal vibration, yet 'cold' as regards their translational and rotational motions, and the study of this has thrown light on the propagation of chain reactions, and the transfer of energy from vibrational to other thermal degrees of freedom.

The method to which I refer may be called 'kinetic spectroscopy': it involves the use of the photochemical technique of flash photolysis, discovered and developed spectroscopically in our Laboratory of Physical Chemistry at Cambridge, as I shall presently describe. First, however, let me say a few words about the basic photochemical principles with which we are concerned.

The light which stimulates chemical reactions extends from the red end of the visible spectrum at 7000 Å to the extreme ultra-violet. In practice, with a few exceptions, direct observation of reaction kinetics is limited by the transparency of quartz to about 1900 Å, though photochemical effects can be inferred from spectroscopic observations in the vacuum ultra-violet as far as 500 Å.

Fundamental Photochemical Principles

The absorption or emission of light by atoms and molecules takes place in terms of 'quanta', and to the photochemist the photon takes the same importance as the atom did to the chemist one hundred and fifty years ago. Photochemistry is the study of the interaction of photons with atoms and molecules.

The magnitude ϵ of the photon or quantum of light is related to its colour, i.e. its wavelength,† and is given by

$$\epsilon = \frac{hc}{\lambda} = h\nu$$

It therefore increases as we pass from red to blue into the ultra-violet.

If every molecule in a gram molecule absorbed a photon the total amount of energy absorbed would be

$$E = N\epsilon = \frac{Nhc}{\lambda}\ (\text{ergs})$$

$$= \frac{6{\cdot}06 \times 10^{23}.6{\cdot}6 \times 10^{-27}.3 \times 10^{10}}{\lambda\ (\text{in cm.})\ \mathcal{J}}\ (\text{cal.})$$

For yellow light	$E = ca.$ 45,000 cal.
For blue light	$E = ca.$ 65,000 cal.
For ultra-violet light (3000 Å)	$E = ca.$ 95,000 cal.

Chemically speaking these are very large amounts of energy.

When a photon of the spectral range with which we are concerned here is absorbed by a molecule,

† h=Planck's constant; c=velocity of light; λ=wavelength; ν=frequency; N=Avogadro's number; $\mathcal{J}$=Joule's equivalent.

only a small proportion gives rise in the first instance to heat in the form of vibrational and rotational displacements of the molecule, and in the case of monatomic substances none of the energy appears initially as heat, although in both cases it may be degraded to heat by secondary processes.

The photon, absorbed by the atom or molecule, brings about a change in the electronic configuration which effectively produces a new atom or molecule of higher energy, changed reactivity and new characteristics. Such an atom or molecule is said to be excited. There are in general more than one energy level, and as many excited states and an atom or molecule may thus absorb more than one wavelength to give characteristic absorption spectra. The study of photochemistry is concerned with the physical and chemical consequences resulting from the absorption of a photon by an atom or molecule.

The photochemist distinguishes three stages in a photochemical process:

(1) The process of light absorption: 'one molecule, one photon'—leading to the excited state.

(2) The primary reaction: the immediate chemical change suffered by the excited molecule, e.g. dissociation:

$$NO_2 + h\nu \rightleftarrows NO_2^* \rightarrow NO + O$$

(3) The secondary reactions—the subsequent 'dark' reactions of the products of the primary process:

$$O + NO_2 = NO + O_2$$

Often the energy absorbed in process (1) does not give rise to reaction; the process may be reversible in which case we get fluorescent emission closely related in structure to the absorption spectrum. Alternatively, the energy of the excited molecule may be degraded to heat by collision and lost.

The maximum life period of an excited molecule or atom is $10^{-8}-10^{-7}$ sec.: whatever is going to happen must take place in that interval, otherwise the reverse process occurs and the energy is rejected as fluorescence. Some molecules when excited are so unstable that they break down in the course of $10^{-13}-10^{-10}$ sec. to give atoms or free radicals or simpler molecules by processes known as optical dissociation and predissociation, as for example:

$$Cl_2 \rightarrow Cl + Cl$$
$$S_2 \rightarrow S + S$$
$$CH_3COCH_3 \rightarrow .CH_3 + .COCH_3$$
$$CH_3COCH_2CH_2CH_3 \rightarrow CH_3COCH_3 + C_2H_4$$

Such processes, especially in simple molecules, may often be recognised spectroscopically by a diffuseness which overtakes the vibrational or rotational structure of the absorption spectrum in the region corresponding to the photochemically active wavelengths.

It may happen also that instead of reacting or losing its energy as fluorescence an excited atom or molecule may collide with an atom or molecule of another species with transference of the bulk of the energy from the one to the other by a radiationless process, causing the second to become excited and to react. Such a process is known as photosensitisation; it is well represented by photosensitive action of mercury vapour in dissociating hydrogen, hydrocarbons, etc.

$$Hg + h\nu(2536\text{Å}) \rightarrow Hg^*$$
$$Hg^* + H_2 = Hg + H + H$$

In other cases the photosensitiser may itself participate in the reaction as with the photosensitised decomposition of ozone by chlorine; in such cases the 'sensitiser' is regenerated intact.

$Cl_2 + h\nu = Cl + Cl$	Primary reaction
$Cl + O_3 = ClO + O_2$	Secondary (chain) reactions
$ClO + O_3 = Cl + O_2 + O_2$	
$ClO + ClO = Cl_2 + O_2$	Sensitiser regenerated

Of the secondary reactions we may distinguish two types—those corresponding to overall endothermic processes in which the energy of reaction is provided directly by the photon, and those whose overall processes are exothermic, in which the light acts, as it were, catalytically, initiating a series of self-propagating reactions able to multiply to explosion, just as a minute spark can set off a great conflagration. The former of these two types is exemplified by the photolysis of nitrogen peroxide already cited in which the maximum yield cannot rise above two molecules of NO_2 reacted per quantum of light absorbed. The latter type comprises all those chain reactions initiated by light, such as the chlorination of hydrocarbons, or the photosynthesis of hydrogen chloride, where the

quantum yield may be as high as 10^6 molecules reacting per quantum absorbed, e.g.

$Cl_2 + h\nu = Cl + Cl$	Primary reaction
$Cl + H_2 = HCl + H$ $H + Cl_2 = HCl + Cl$	Secondary (chain) reactions repeated n times
$Cl + Cl = Cl_2$	Chain termination
$nH_2 + nCl_2 + h\nu = 2nHCl$	Overall reaction

The principles of photochemical reaction which I have just summarised were first conceived some fifty years ago through the work of Warburg, Bodenstein, Henri and Weigert and took final shape through the work of others who followed. Into the whole framework have been fitted innumerable photochemical and thermal reactions whose postulated mechanisms, involving atoms free radicals or excited species, are entirely derived from the circumstantial evidence afforded by spectroscopic observations and quantitative measurements involving photochemical kinetics, and end products. In general, the consistency of the mechanisms within the framework is so good as to lead to confidence in our conclusions, but the absence of any objective proof of the existence of the postulated intermediates has constituted a permanent challenge to the photochemist, and has sometimes given rise to criticism from unbelievers which weakened his position.

Flash Photolysis

It was for this reason that in 1946 we decided to break new ground by endeavouring to obtain direct spectroscopic evidence for the free radicals postulated as intermediates in photochemical reactions. This was made possible by the discovery by Porter and myself[1] that very large measures of photolysis (sometimes complete) could be achieved by the application of a powerful light flash to suitable reactants, such as nitrogen peroxide, iodine, or acetone, contained in a quartz vessel. These early flashes produced by discharging a bank of condensers through argon were of 1–2 milliseconds duration and dissipated up to 10,000 Joules of energy, and it seemed obvious that if free radicals were produced in the reactions, they must momentarily have been at such very high concentrations as to invite efforts to photograph their absorption spectra. This was achieved in the first instance by Porter[2] in 1949, who, using a second flash as a photographic source triggered mechanically at short intervals after the first by the method of Oldenburg, was able to demonstrate the dissociation of chlorine and to obtain the spectrum of the CS radical by the photolysis of carbon disulphide. This early success was followed by the development of the technique: shorter photolysis flashes of 100 microseconds duration and of 1000–3000 Joules were devised, and shorter intervals between the photolysis flash and spectro-

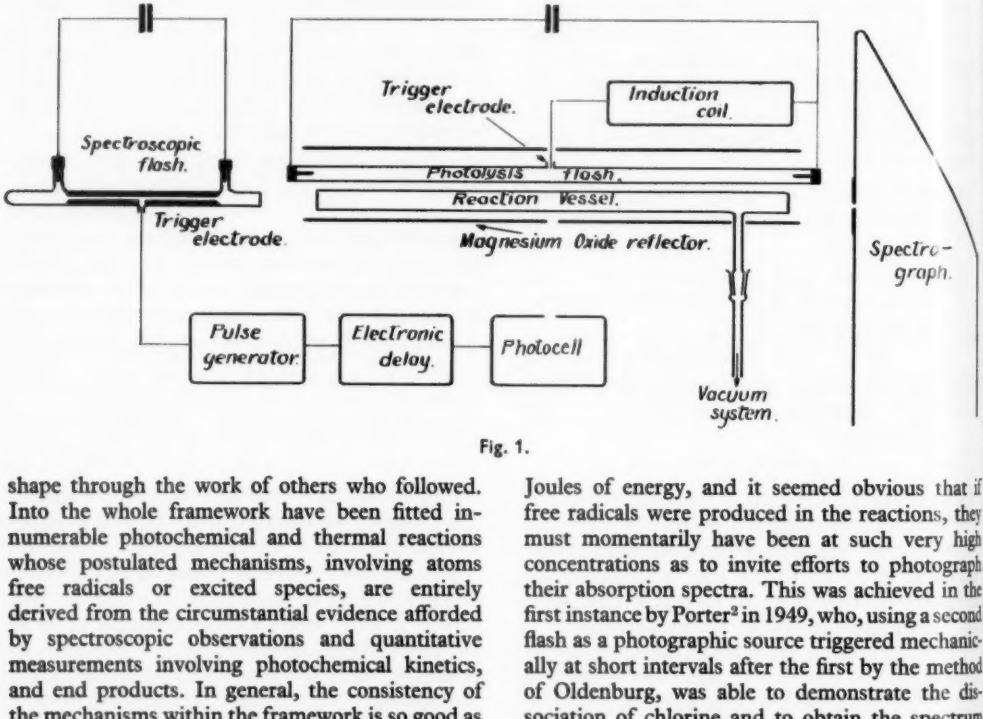


Fig. 1.

scopic flash were achieved by using electronic delay circuits capable of precision timing to a few microseconds. That which follows is a description, with reference to Fig. 1, of the improved apparatus described by Norrish, Porter and Thrush,[3] which is basically typical of the method used today.

The Apparatus. By the discharge of a bank of condensers through an inert gas such as Krypton at about 10 cm. pressure, powerful flashes dissipating some 1000 to 3000 Joules of energy may be produced. The silica flash tube is 50 cm. in length and 1 cm. internal diameter, and the discharge takes place between thick tungsten electrodes. The energy dissipated is given by

$$E = \tfrac{1}{2}CV^2$$

where C is the capacity and V the potential between the electrodes. Ideally for a given energy the shortest flash is obtained by making the capacity as low and the voltage as high as possible, while at the same time reducing to a minimum the self-inductance of the system. For a tube 50 cm. in length we generally use a capacity of 40 μF and a voltage of 10 kV. giving a flash energy of 2000 Joules and about 50 μsec. duration.

The flash is applied to the contents of a quartz reaction vessel 50 cm. long and 2 cm. diameter with plane end plates, lying parallel and close to the flash tube; the whole is surrounded by an aluminium tube coated on the inside with magnesium oxide to act as a reflector. The second lamp giving the spectroscopic flash is arranged to throw a beam through the length of the reaction vessel by means of which the absorption spectrum of the contents of the tube is photographed by a Littrow spectrograph (Hilger 478). The spectroscopic flash of 100 Joules and 10 μsec. duration is obtained by discharging a 2 μF condenser at 10 kV. through a capillary tube about 10 cm. long containing Krypton or other inert gas at about 10 cm. pressure. It gives a fairly continuous spectrum which allows an absorption spectrum to be photographed with one flash.

It is fortunate that neither lamp is discharged until a pilot or trigger current from an induction coil is passed, and this makes it possible by means of a photocell and a suitable calibrated electronic delay circuit to cause the flash from the first lamp (the photoflash) to discharge the second (the specflash) at suitable controlled intervals varying from a few microseconds to seconds. Thus it is possible by taking a series of separate spectrum photographs at increasing intervals of time to observe the growth and decay of any identifiable intermediate species in the reaction vessel over periods of a few milliseconds, and further by means of methods of plate photometry to put these observations on a quantitative basis.

It soon became apparent that the early results of flash photolysis in the gaseous systems which I have previously exemplified were vitiated by a great rise of temperature, which resulted in thermal as well as photochemical dissociation. This arises from the fact that when the intense flash is applied to a suitably absorbing system such as chlorine, or nitrogen peroxide, the absorbed light energy is rapidly degraded to heat: it may be calculated that a reactant at a pressure of 1 mm. absorbing one-thousandth of the emitted energy will instantaneously reach a temperature measured in some thousands of degrees. Only if a relatively large excess of inert gas (say 500 mm. pressure) is present to act as coolant, or the process is carried out in solution, can this temperature rise be kept in check, and so limited to a few—say ten degrees in the case of a gaseous system. Thus under the adiabatic conditions resulting from lack of temperature control thermal cracking or explosion as well as photolysis may be induced in suitable systems and the method of kinetic spectroscopy provides a valuable means for the observation of the rapid elementary reactions of free radicals or atoms occurring in explosive media initiated photochemically.

We thus have a comprehensive method which can be applied to 'instantaneous' reactions in the gas phase both under adiabatic and isothermal conditions, and also to reactions in solution. It should be emphasised that, since the spectral spread of the photolysis flash while fairly continuous is limited by the transparency of quartz to 1900 Å, none of the phenomena of ionisation characteristic of the vacuum ultra-violet are involved in the reactions studied.

I shall now endeavour to give briefly some typical examples of the various types of reaction studied by the method of kinetic spectroscopy.

Adiabatic Reactions

To illustrate the thermal effect of the flash when no inert gas is added as coolant, we may cite the

remarkable case of sulphur dioxide.[4] Plate I (*a*) shows a series of photographs of the absorption spectrum of sulphur dioxide at 1 mm. pressure taken at increasing intervals after the photoflash. It is seen that the characteristic absorption disappears completely for 1 millisecond and is then gradually regenerated within the course of say 20 milliseconds, the final state being the same as the first. There is no appreciable photolysis of SO_2 which is feebly sensitive photochemically only below 2200 Å, and added to this, when an excess of nitrogen is present as coolant the effect is completely suppressed: it is thus truly thermal in origin. It was at first suggested that the disappearance of the spectrum on flashing as in the case of that of chlorine under similar circumstances is to be explained by the supposed cooling effect of the walls on the strongly heated gas in producing a very high radial pressure gradient, so that the central core of the reaction tube is almost completely devoided of gas. That this is not true is proved by the observations of Oldershaw who, by extending the observations to shorter wavelengths, showed that a new transient band spectrum is generated between 2250 and 2400 Å immediately after flashing, together with a strong continuum below 2250 Å (Plate I (*b*)). The continuum which replaces the SO_2 spectrum persists until the original spectrum is regenerated: it is completely complementary to it in time. On the other hand, the transient band spectrum has been identified as that of the free radical SO; it agrees with the bands predicted by Martin's results for the known emission bands of SO at longer wavelengths. Its duration is markedly reduced by the addition of a little oxygen as would be expected if the SO radical were oxidised under these circumstances. None of these effects at short wavelength could possibly be observed if the disappearance of the SO_2 spectrum were due to the establishment of a pressure gradient as first suggested.

It may be estimated that on flashing without coolant the temperature of the sulphur dioxide is raised momentarily to 2500° C. There seems to be no other explanation than that some form of thermal isomer is generated reversibly at high temperature giving the continuous spectrum which reverts to that of normal SO_2 as the gas cools

$$SO_2 \rightleftarrows SO_2'$$

It may be suggested that this corresponds to some form of metastable triplet state or bond dissociation, e.g. $O{:}\dot{S}{-}\dot{O}$, and that the SO radical is derived from the photolysis or pyrolysis of this isomer rather than the normal SO_2 molecule.

These observations, depicted in Plate I (*a*) and (*b*), are important to the understanding of the reactions of sulphur dioxide at high temperatures as well as the characterisation of the spectrum of the SO radical, which we have also obtained by the flash photolysis of sulphur trioxide under isothermal conditions.

Explosive Processes

The importance of flash photolysis to the chain processes of combustion lies in the fact that it can be used as a means of administering a quasi-adiabatic shock to the potentially reactant system as well as a source of the free radicals or atoms essential to the initiation of the reaction chains. With systems showing strong absorption such as formaldehyde[5] or hydrogen sulphide[6] and oxygen, for example, either slow combustion or explosion can be induced according to the strength of the photolysis flash, and after an induction period of usually a few hundred microseconds, free radicals such as OH and HCO in the case of formaldehyde, and HS, OH and SO in the case of hydrogen sulphide, become apparent. By studying the rise and decay of these radicals against time under conditions of varying temperature and partial pressures of reactants, or added inert gases, much may be learned about the mechanism of the slow and explosive processes of these reactions which, when combined with classical kinetic studies, make possible a more complete and more definite picture of the processes than was possible before.

For systems composed of hydrogen, carbon monoxide or hydrocarbons and oxygen, however, which do not absorb the radiation of the photolysis flash there is no response since neither primary photolysis nor temperature rise can be induced; in such cases a photosensitiser is essential. Nitrogen peroxide absorbs strongly throughout the visible and ultra-violet and is photolysed by light of wavelength less than 4100 Å according to the equation

$$NO_2 + h\nu = NO + O$$

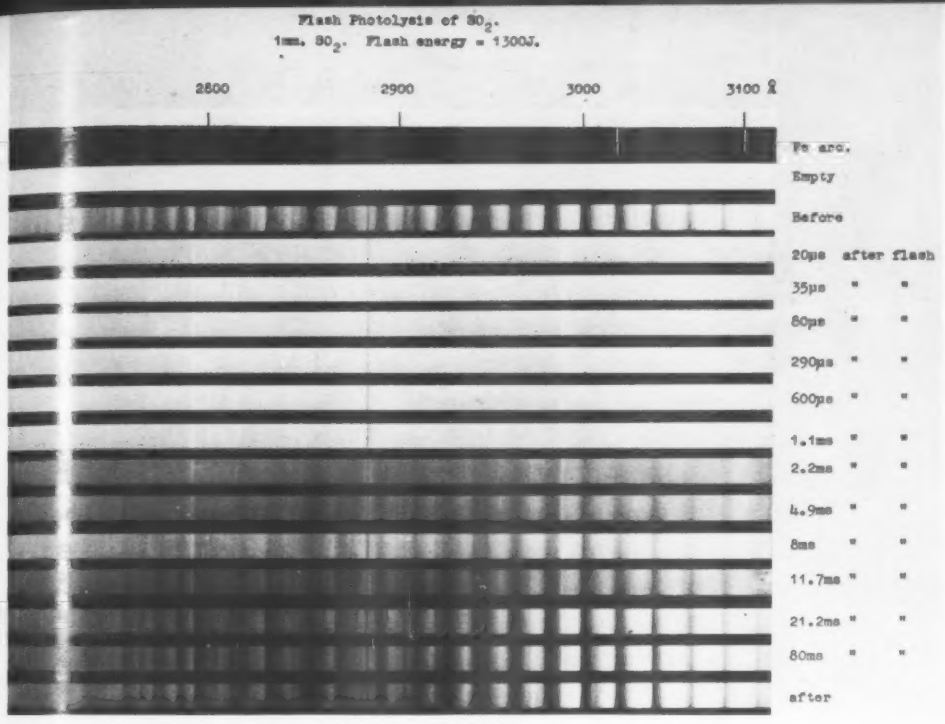


PLATE Ia

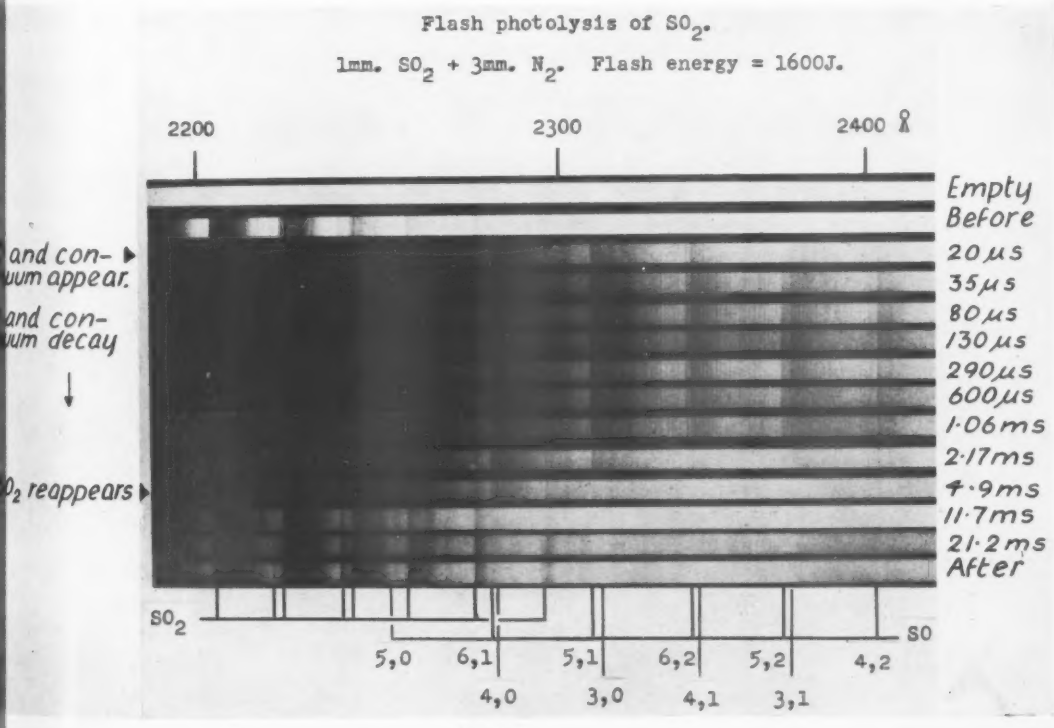


PLATE Ib

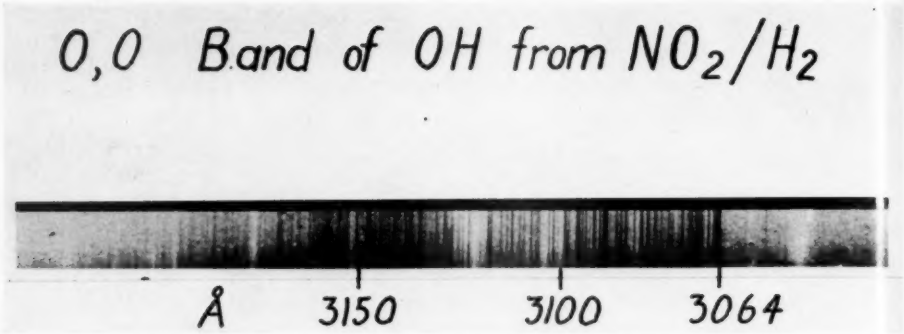


PLATE IIa—0·0 band of OH obtained by flashing a mixture of 2 mm. NO_2 and H_2.

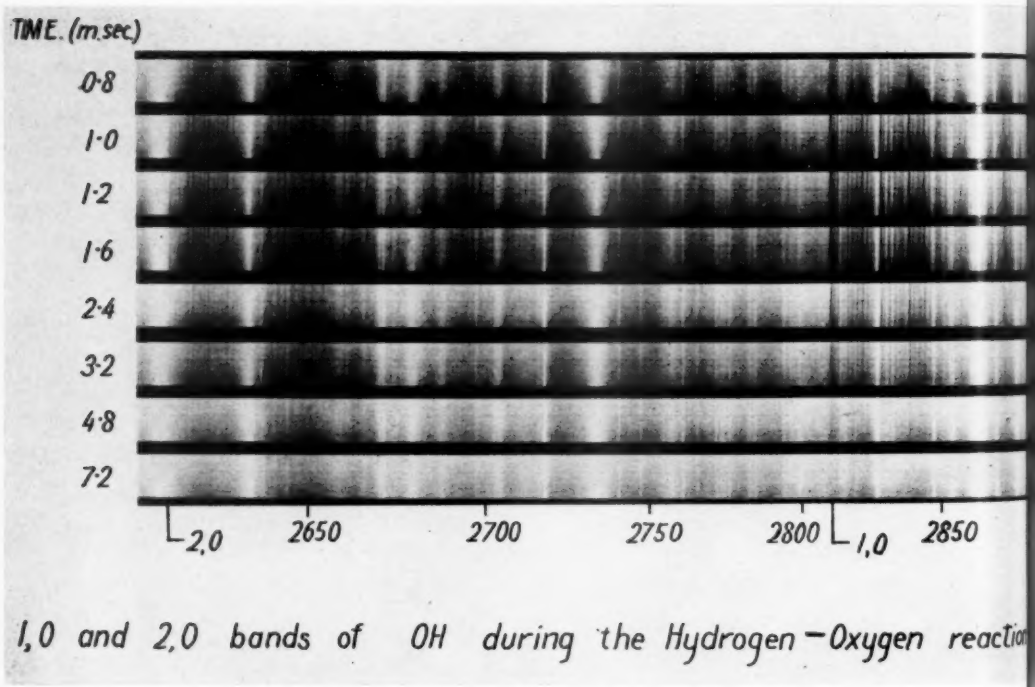


PLATE IIb—Variation of intensity of OH absorption spectrum during explosion, as shown by 1·0 and 2·0 bands. P[H_2]=10 mm. P[O_2]=5 mm. P[NO_2]=0·75 mm.

(a) Abs
(b) Abs
(c) Abs

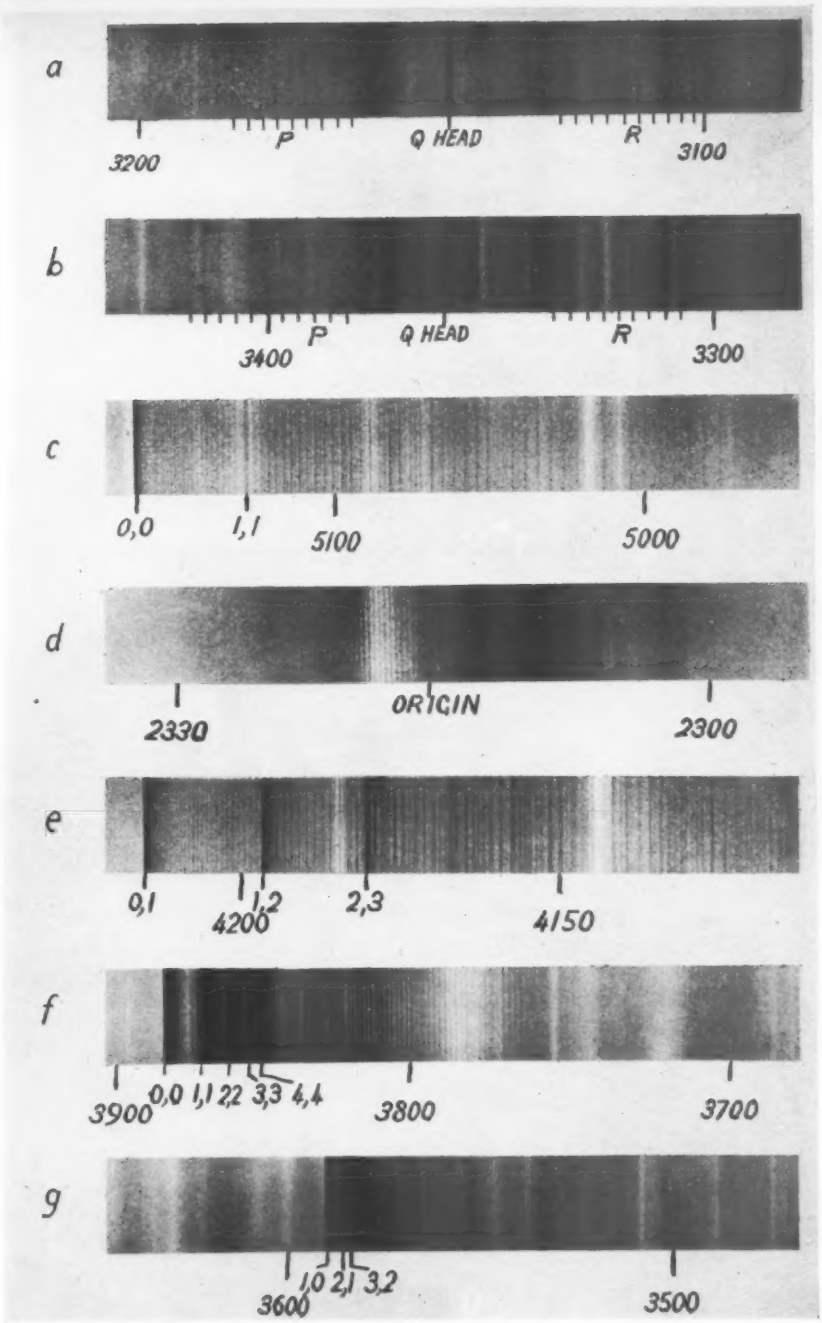
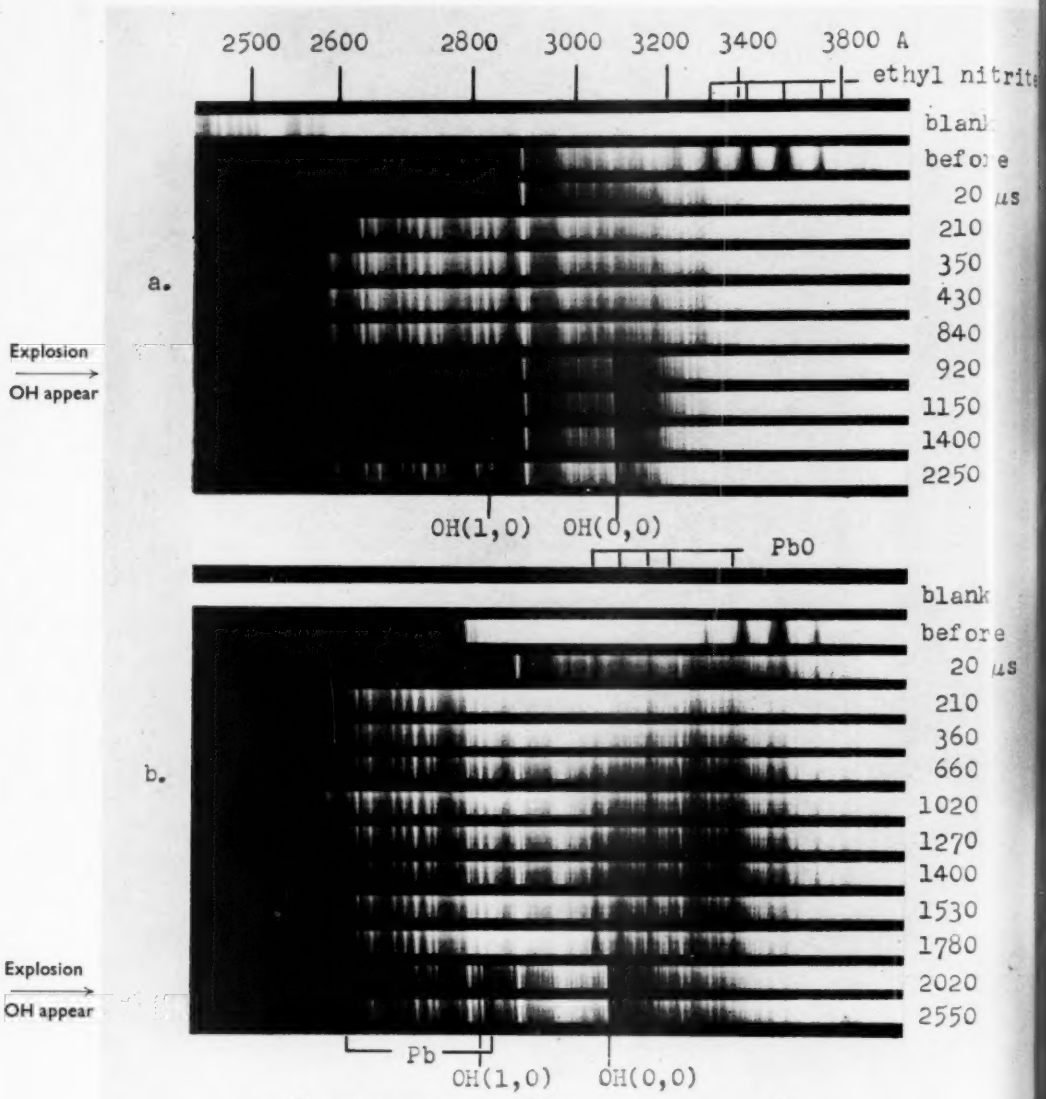


PLATE III

(*a*) Absorption spectrum of CH: $^2\Sigma^+ - {}^2\Pi$ system.
(*b*) Absorption spectrum of NH: $^3\Pi - {}^3\Sigma$ system.
(*c*) Absorption spectrum of C_2: 'Swan Bands'.
(*d*) Absorption spectrum of C_2: 'Mulliken Bands'.
(*e*) Absorption spectrum of CN: $^2\Sigma - {}^2\Sigma$ 1·0 progression.
(*f*) Absorption spectrum of CN: $^2\Sigma - {}^2\Sigma$ 0·0 progression.



Spectra against time.

a) 3 mm. C_2H_5ONO + 3 mm. C_7H_{16} + 50 mm. O_2

b) 3 mm. C_2H_5ONO + 3 mm. C_7H_{16} + 50 mm. O_2 + 0.14 mm. TEL

Flash energy 1000 J.

PLATE IV—Antiknock effect of tetra-ethyl lead.

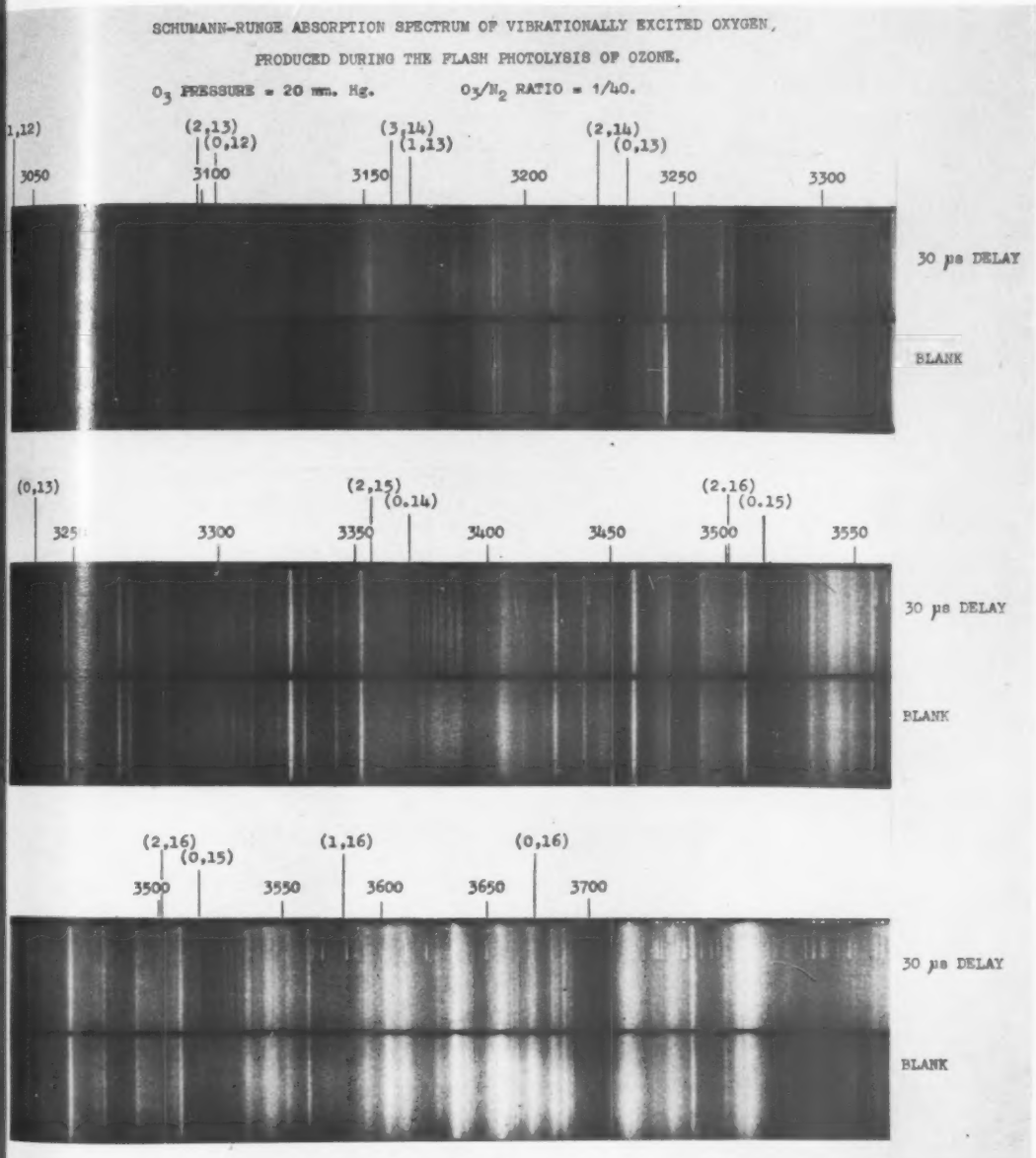


PLATE V—Schumann range absorption of vibrationally excited oxygen produced during the isothermal flash photolysis of ozone.
O_3 pressure = 20 mm. Hg; O_3/N_2 ratio = 1/40.

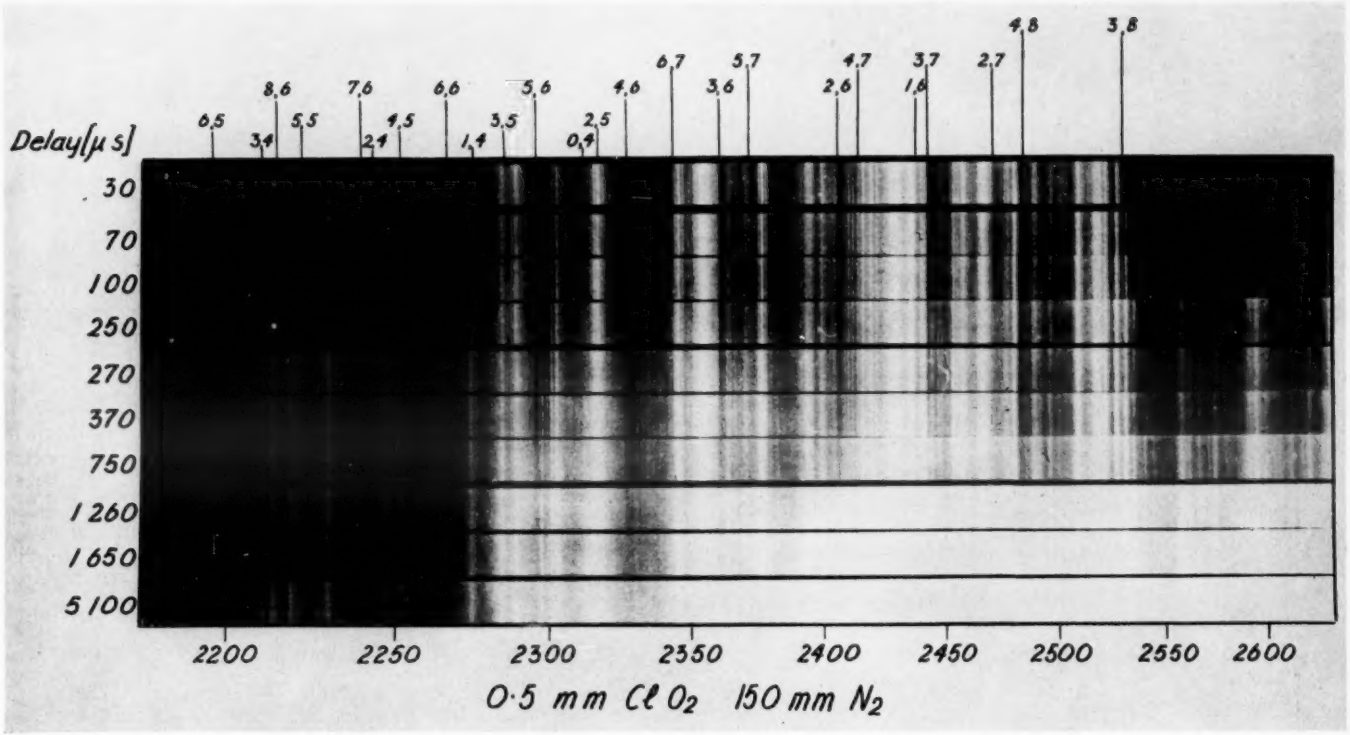


PLATE VI—Decay of vibrationally excited oxygen produced by the isothermal flash photolysis of ClO_2.

Fig. . Decay of NO $^2\Pi$(v = 1) with time.
Pressure of NO = 5 mm. Hg; pressure of N_2 = 600 mm. Hg. Flash energy = 1600 Joules.

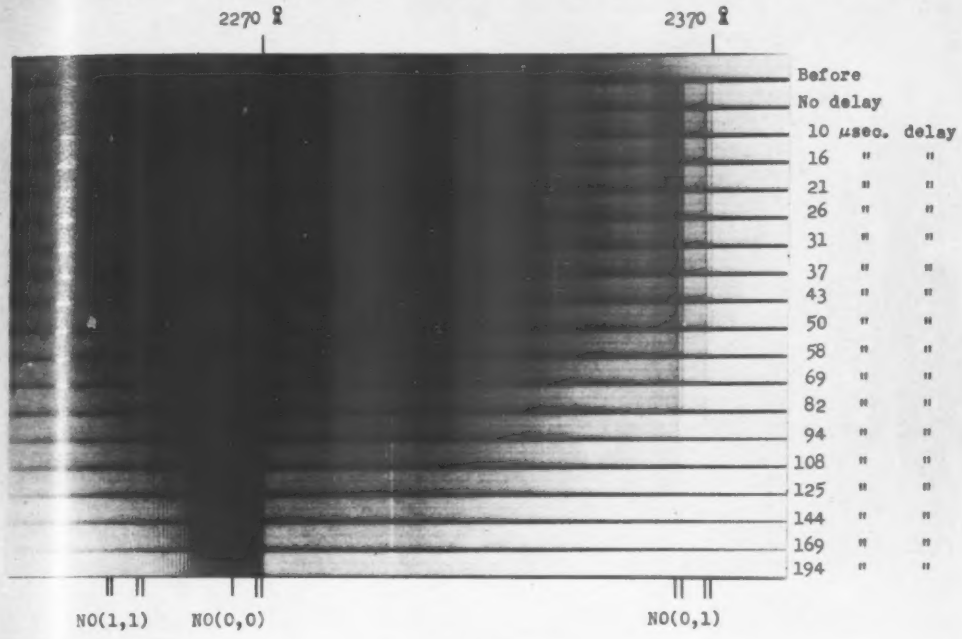


PLATE VIIa

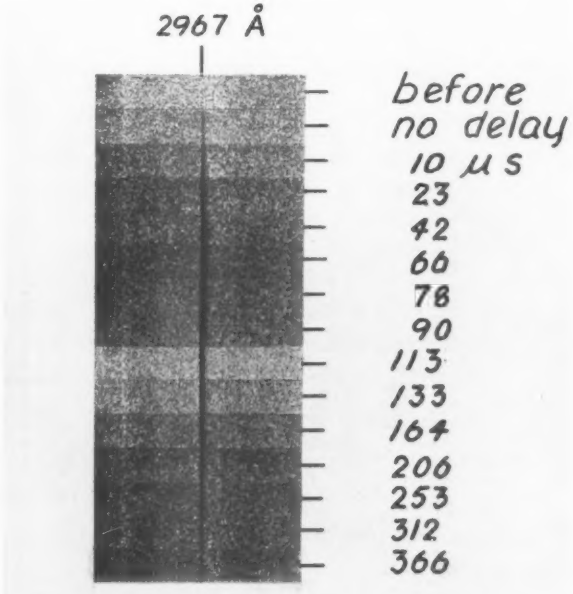


PLATE VIIb

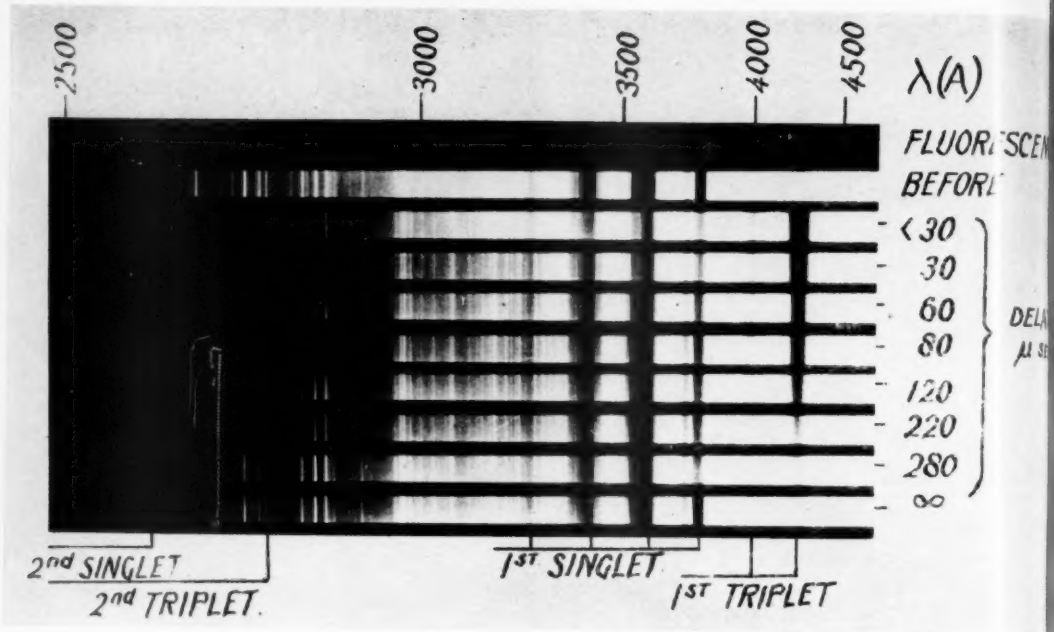


PLATE VIII*a*—The decay of the triplet state of anthracene produced at the expense of the normal (singlet) state by flash photolysis (Porter).

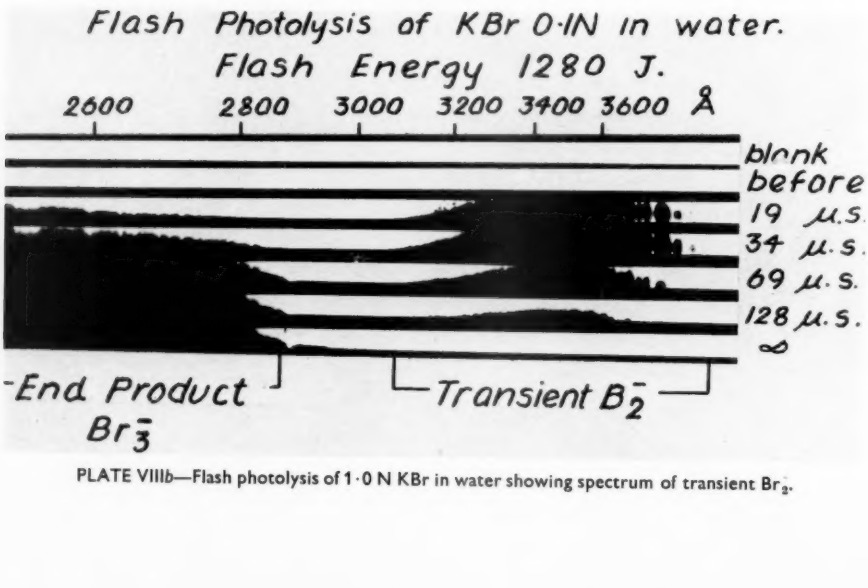


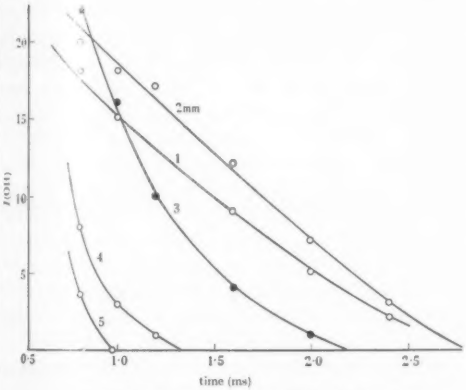
PLATE VIII*b*—Flash photolysis of 1·0 N KBr in water showing spectrum of transient Br_2^-.

It is therefore an ideal substance, not only as an absorbent of radiation to give rise of temperature, but also as a source of oxygen atoms capable of acting as chain initiators. Added in small quantities to mixtures of hydrogen, or hydrocarbons and oxygen, it acts as a most efficient sensitiser. In addition for similar reasons we have found that alkyl nitrites make excellent photosensitisers for hydrocarbon combustion.

In Plate II (*a*) is shown part of the absorption spectrum of the OH radical produced by flashing a mixture of 2 mm. H_2 + 2 mm. NO_2, a result which constitutes proof of the elementary reaction

$$O + H_2 = OH + H$$

In Fig. 2 the decay of the OH radical spectrum is plotted as a function of time, the decay being more rapid the greater the excess of hydrogen over



OH intensity against time: effect of $P(H_2)$; $P(NO_2)$ = 2 mm. All figures against curves show pressures in mm.

Fig. 2.

the equi-molecular stoicheiometric mixture of H_2 + NO_2. This may be taken as evidence of the elementary reaction:[7]

$$H_2 + OH = H_2O + H$$

Finally, it is found that the rate of decay of OH when there is no excess of H_2 to remove it is greatly reduced by adding increasing amounts of inert gas (N_2) showing how its removal by diffusion to the wall of the reaction vessel is hindered by increase of pressure. Thus three elementary reactions previously deduced from the kinetics of the hydrogen oxygen reaction are objectively demonstrated.

In Plate II (*b*) is shown a record of an explosion of $2H_2 + O_2$ sensitised by NO_2 in which the explosion as demonstrated by the growth and decay of OH can be clearly followed in both the 1·0 and 2·0 bands. Although the photograph was taken in the early days with a relatively long flash, an induction period of about 0·8 millisecond is evident, while the disappearance of the radical takes about 7 milliseconds.[7]

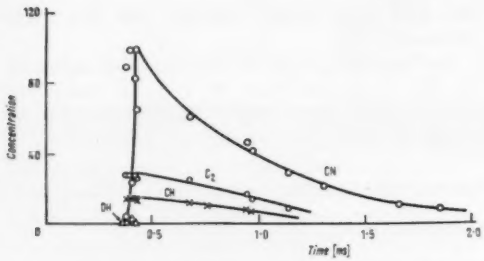
An essential feature of flash photolysis as a means of studying combustion is that by its means it is possible to generate approximately homogeneous explosions, so that if the reaction tube is ½ m. long, we virtually have a flame front which is ½ m. thick and free radicals with suitable absorption spectra readily become visible spectroscopically.

It therefore happens that in the method of kinetic spectroscopy we have a unique method for observing some of the reactions in the flame and pre-flame stages of combustion which would not otherwise be visible. I shall limit myself to referring to some of our earlier work based mainly on experiments with acetylene.[3] The further development of this line of investigation involving the hydrocarbons of petroleum and the effect of additives on their mechanism of combustion has proved most fruitful.[8, 9]

Plate III shows some of the radical spectra observed in absorption in the explosive combustion of acetylene, ethylene, methane and ethane; most prominent among these in addition to the OH radical are the CN bands (derived from the NO_2) the CH, C_2 and NH bands. In addition the C_3 radical was detected for the first time in absorption being identified by the '4050 Å bands' previously known in cometary emission. In Figs. 3 and 4 are depicted curves showing the waxing and waning of the free radicals mentioned above in the explosive combustion of acetylene, as measured on an arbitrary scale by plate photometry using the two-path method. The appearance of these radicals is greatly dependent on the composition of the explosive mixture, being apparently conditioned by the stoicheiometric equation of Bone[10]

$$C_2H_2 + O_2 = 2CO + H_2$$

according to which, if the fuel be in excess of the



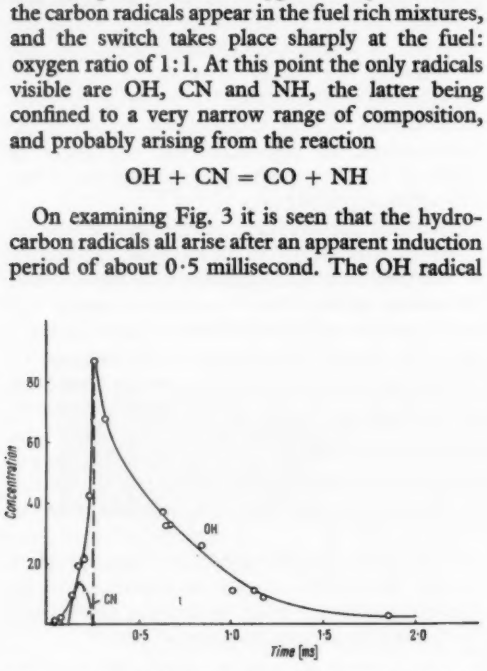
Radical concentrations against time; $P(C_2H_2) = 13$ mm, $P(O_2) = 10$ mm, $P(NO_2) = 1{\cdot}5$ mm.

Fig. 3.

1:1 ratio with oxygen, free carbon is formed as smoke, while if the mixture be oxygen rich, steam is formed. Our results strongly support Bone's results as is shown by plotting the maxima of the free radical curves against mixture composition (Fig. 5). Counting nitrogen peroxide as oxygen for the purpose of combustion, it is seen that the OH radical is predominant in oxygen-rich systems while the carbon radicals appear in the fuel rich mixtures, and the switch takes place sharply at the fuel: oxygen ratio of 1:1. At this point the only radicals visible are OH, CN and NH, the latter being confined to a very narrow range of composition, and probably arising from the reaction

$$OH + CN = CO + NH$$

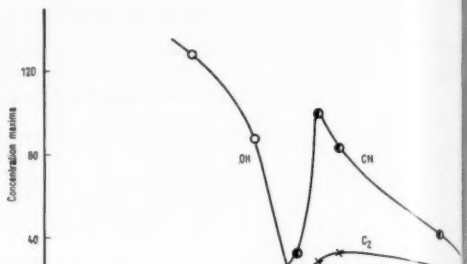
On examining Fig. 3 it is seen that the hydrocarbon radicals all arise after an apparent induction period of about 0·5 millisecond. The OH radical



Radical concentrations against time; $P(C_2H_2) = 10$ mm, $P(O_2) = 10$ mm, $P(NO_2) = 1{\cdot}5$ mm.

Fig. 4.

under these conditions is barely visible but in all cases is seen slightly before the other radicals. If a tracer compound such as benzene be added to the mixture, its spectrum completely disappears before the end of the induction period and further, the bands of nitric oxide visible immediately before the end of the induction period show a high rotational temperature of over 2000° C. These observations lead us to the conclusion that at the instant when the carbon radicals are released the explosion is over—that we are in fact witnessing the after cracking of excess acetylene in the heat of the flame. The induction period undoubtedly marks the exponential development of pre-flame



$P(O_2) = 10$ mm, $P(NO_2) = 1{\cdot}5$ mm.

Fig. 5.

reactions, with temperature rising very strongly at the end, and the OH radical—the only intermediate species visible—appearing immediately before the explosion. In oxygen-rich mixtures, typified by Fig. 4, the explosion is marked by the peak of the CN radical while the peak of OH absorption appears later as a result of the after burning of the hydrogen. Here again the OH radical is visible during the induction period, showing that it is involved in the pre-flame reactions.

The effect of additives to explosive combustion is illustrated in Plate IV which illustrates the photochemical ignition of heptane with and without the addition of lead tetraethyl.[8] The incubation period of the reaction is finalised in both cases by the appearance of the OH radical spectrum, at

which point the stoicheiometric combustion is complete; and the fact that the incubation period is increased more than two-fold by the additive, with the appearance of the lead oxide bands in absorption has suggested that the anti-knock effect of lead tetraethyl is exercised in the pre-flame period and is associated with the production of lead oxide in the gaseous phase, and its dissociation to gaseous lead at the instant of ignition.

Free Radicals and Isothermal Gas Reactions

In addition to the free radicals referred to above, which have been produced in explosive processes, several others derived from primary photochemical processes have been identified by their absorption spectra under isothermal conditions. Mention may be made of the HCO radical[11] produced by the photolysis of aldehydes, the HS and HS_2 radicals from hydrogen sulphide,[12] the N_3[13] radical from hydrogen azide, the NH_2[14] and NH[15] radicals from ammonia and the PH_2,[16a] PH and PO [16b] radicals from phosphine. One of the most extensively studied radicals the ClO radical is obtained by the photolysis of chlorine dioxide[17] or chlorine monoxide[18] as well as by the photochemical reaction between chlorine and oxygen[19] or ozone.[20] Its transient spectrum which lasts only a few milliseconds has been analysed by Porter and Wright and its dissociation energy accurately determined, while the bimolecular decay to Cl_2 and O_2 can be readily followed. Recently Herzberg has isolated the CH_3 and CH_2 radicals[21] by flash photolysis and photographed their absorption spectra in the vacuum ultra-violet. Flash photolysis indeed provides a happy hunting ground for the spectroscopist and theoretical chemist interested in the ultimate detail of structure and energy levels of molecules and free radicals.

The method of kinetic spectroscopy not only makes possible the identification of free radicals produced by photolysis but also gives information about their stability and reactivity. I will briefly describe the flash photolysis of ozone to illustrate this.

The photolysis of ozone in the ultra-violet has been characterised as a chain reaction by Heidt and Forbes, the quantum yield reaching 7 under favourable conditions.[22] This was explained by the scheme proposed by Beretta and Schumacher[23] involving excited oxygen molecules, the essential features of which are

$$O_3 + h\nu \rightleftarrows O_2 + O$$
$$O + O_3 = O_2 + O_2^*$$
$$O_2^* + O_3 = 2O_2 + O$$
$$O + \text{wall} = \tfrac{1}{2}O_2$$

Owing to the simplicity of the reaction we are limited to a scheme of this kind, but the nature of the excited oxygen molecule was not clear, though it was generally considered to be an unidentified excited electronic state.

By the flash photolysis of pure ozone in the presence of excess inert gas, we were however able to detect the spectrum of vibrationally excited oxygen in absorption (Plate V).[24] This spectrum consisted of an extension towards longer wavelengths of the spectrum of normal oxygen known previously only in the vacuum ultra-violet (the Schumann Runge bands) and indicated that the oxygen molecule is highly vibrationally excited, but otherwise 'cold' as regards rotation and translation. Moreover, up to 17 quanta were detected in the vibration, corresponding to more than half the thermal energy of the reaction†

$$O + O_3 = O_2 + O_2$$

This remarkable fact brought to light a new generalisation which we were able to establish, namely that with reactions of the type

$$A + BCD = AB + CD$$

a large fraction of the energy of reaction appears unequilibrated as energy of vibration in the newly formed bond AB—a circumstance of great importance to the understanding of the mechanism of chain reactions. In the case cited above, molecules of 18, 19, 20, etc., quanta of vibration are conspicuously scarce or completely absent; these are the molecules with just enough energy to bring about the endothermic reaction

$$O_2^* + O_3 = 2O_2 + O$$

and so to propagate the chain. They are immediately removed by this reaction. On the other hand, oxygen molecules with 17 quanta or less are not

† The oxygen atom derived from the ultra-violet photolysis of ozone has been proved to be in the first excited electronic state (^1D).[20,25] The argument unfortunately cannot be reproduced here.

sufficiently energised. They have a life long enough to be seen in absorption, and their decay with time can be observed.

Plate VI shows the decay of similarly excited oxygen molecules produced by the flash photolysis of ClO_2 and derived from the reactions

$$ClO_2 + h\nu = ClO + O$$
$$ClO_2 + O = ClO + O_2^*$$
$$2ClO = Cl_2 + O_2$$

a process closely analogous to the ozone reaction.

Here again we have an example of the generalisation cited above. Many others have come to light, of which we may mention the following:[25]

$$H + O_3 = OH^* + O_2$$
$$Cl + O_3 = ClO^* + O_2$$
$$Br + O_3 = BrO^* + O_2$$
$$O + H_2 = OH^* + H$$
$$O + H_2O = OH^* + OH$$
$$O + CH_4 = OH^* + CH_3$$
$$O + HCl = OH^* + Cl$$
$$O + NH_3 = OH^* + NH_2$$

In all cases but the first, which was discovered by McKinley, Garvin and Boudart by an alternative method, we have observed the vibrationally excited product spectroscopically.† Always it is the molecule containing the newly formed bond which is stimulated vibrationally, taking preferentially a large part of the exothermic energy of the reaction.

Energy Transfer

In the cases cited above the vibrationally excited molecule is produced by chemical reaction. In addition we have been able to populate the vibrationally excited levels of the electronic ground state of nitric oxide without reaction.[26] This depends on excitation to an upper electronic state followed by fluorescence as shown in the diagram (Fig. 6). In Plate VII (*a*) is shown the decay of the vibrating NO molecule produced in this way. It is possible to put the measurements on a completely quantitative basis and to determine the absolute efficiencies of collisions with various other molecules in removing energy from the vibrational to the other degrees of freedom. This

† The oxygen atoms cited in the equations listed are derived from the photolysis of ozone, and are in the ^1D electronic state.[20,25]

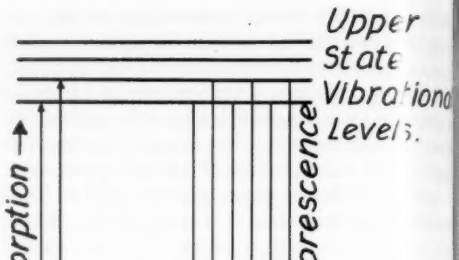


Fig. 6.—Diagrammatic excitation of lower levels by fluorescence

process is known as relaxation, and its measurement has not before been possible because we were not previously able to provide a finite concentration of molecules exclusively stimulated in one vibrational degree of freedom. An accurate understanding of the mechanism of collisional deactivation of this kind is of great importance to the theory of reaction kinetics in general.

Recently Callear has succeeded in populating the $^3P_0$ state of the mercury atom by flash irradiation,[27] and to obtain its absorption spectrum. The rate of decay of the spectrum, of which one line is shown in Plate VII (*b*), can be measured photometrically, and the relative efficiencies of colliding molecules in degrading the electronic energy of this metastable triplet state determined. Observations of this kind will be of great importance to the understanding of the mechanism of photosensitised reactions to which I have already referred.

Reactions in Solution

Many reactions in solution may be studied by flash photolysis. In all such cases the system remains strictly isothermal. We may mention in particular the important investigations by Porter and his colleagues of the triplet or diradical state of aromatic hydrocarbons and dyestuffs.[28] These metastable states may be readily populated by flash irradiation, and are highly reactive. In particular, their study is very relevant to the fading

of dyes by light, and to many photochemical reactions of complex molecules dependent on the primary generation of diradicals, such as the initiation of polymerisation.[29] In Plate VIII (*a*) the generation and decay of the triplet state of anthracene, which is typical of many similar aromatic hydrocarbons, is shown.

Plate VIII (*b*) is typical of the remarkable transient spectra observed on flashing alkali halides,[30] identified as due to the intermediate X_2^- ion formed in the electron transfer processes leading to the X_3^- ion. This reaction is typical of a wide range of electron transfer reactions in solution which are available for study by kinetic spectroscopy.

The simple reactions which we have discussed above are typical of many others. We have already seen how they can give information about the mechanism of combustion, and so suggest means by which these processes can be controlled. This is not only true of hydrocarbons. It applies to the combustion for example of ammonia, hydrazine, hydrogen sulphide and aldehydes with oxygen or ozonised oxygen, and there is a wide and inviting field for the study of additives.

The very short ultra-violet rays of the sun which do not penetrate our atmosphere, bring about reactions in the upper atmosphere involving atoms and free radicals of the utmost importance to the geochemist, and much information can be obtained about these in the laboratory by the methods I have described. Thirty kilometers above the earth, oxygen is dissociated into atoms, and these form ozone by reacting with oxygen molecules. This produces a blanket of ozone round the earth, which absorbs the radiation of the sun of wavelength less than 2500 Å and as we have seen is destroyed in the process. Thus there is a stationary concentration of ozone produced which is being formed and destroyed at equal rates, and were it not for this protective canopy all life on earth would be destroyed by the short-wave radiation which it excludes. We have seen that the photolysis of ozone involves the generation of highly vibrating oxygen molecules showing an extension of the Schumann spectrum of oxygen into the region of the quartz ultra-violet, nearly as far as the visible spectrum (see Plate VI). One might predict that spectroscopic observation of the light reflected from the moon at sundown, would under favourable conditions of observation show evidence of the same spectral bands. The reaction of ^1D oxygen atoms derived from the photolysis of ozone may also in part be responsible for the emission of the night sky. For example, Meinel has observed the vibration rotation spectrum of OH, the lower levels of which may in part be due to the reaction

$$O(^1D) + H_2O = OH + OH^*$$

The photolysis of water, ammonia and methane which are also present in the upper atmosphere should produce H atoms and free radicals of which the former can react with ozone to give highly excited OH radicals

$$H + O_3 = OH^* + O_2$$

All these reactions are of the highest meteorological importance and are in principle studied by flash photolysis.

It is now believed that our primitive atmosphere was reducing, composed mainly of hydrogen, together with methane, hydrogen sulphide, water, carbon monoxide and ammonia, similar to the atmospheres of the major planets as we see them today. If the solar system had a uniform origin there must have been influences which changed our atmosphere and that of Mars from reducing to oxidising. The first is the progressive loss of hydrogen from our relatively weak gravitational field. The second is the photolysis of water and the other compounds, leading to the formation of formaldehyde and oxides of sulphur, phosphorus and nitrogen, which on interaction, according to the fascinating views of Urey[31] and Oparin,[32] deposited the primordial organic scum on the earth and provided the necessary medium for the evolution of life. Many of the reactions involved in this brief survey can be studied by flash photolysis. Others such as the photolysis of water, methane and other hydrocarbons lie outside its scope, and provide a challenge to extend this powerful method to those shorter wavelengths of the ultra-violet which at present escape us.

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THE SENSES AND THE SCIENCES*

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No one who studies the history and development of science can fail to be struck by the continual interplay of the practical arts, crafts and technologies and the theories and development of thought about the world of which we are ourselves a part; to which we have now abrogated the word science. This interplay is now more than ever to the fore; practical men today appreciate the value of the scientific basis of their technologies, and this has assisted the rapid development of these which we see everywhere. Many examples spring to mind of new technologies born of the human brain's powers of invention when guided by scientific method, and its ability to guide natural forces whether of the wind, the atom or the electron, by learning the crafts of technology. Faraday's little dynamo that prompted the remark of the lady of 'what use is it Mr. Faraday?' and his reply, 'Madam, of what use is a baby?' shows a vision of the possibilities of electric power, but even he would have been, perhaps, astounded at the revolution of human life it would soon produce and is still producing.

If we follow the steps of our ancestors in science we see a continual struggle to overcome the limitations of unaided human senses, for instance in the invention of the telescope and microscope to extend the powers of the eye, or the electroscope or compass to detect components of the environment that do not affect the senses directly. But more important still are the instruments, meters, by which number is assigned to phenomena, and a quantitative abstraction of the phenomena retained, recorded and communicated to others.

Nowadays scientific instruments are often very complex and often used in tandem—one reading another. Moreover, two sets of instruments must be used in experiments; an interfering instrument to produce a change, and an observing instrument to record what results. Observational sciences such as astronomy could not have developed without a foundation of experimental science. Each instrument has its limitations; its laws must be understood for it to be used successfully. It would be silly to try to take the temperature with a barometer —though instruments to measure temperature or pressure may both have glass tubes filled with mercury.

Every instrument is constructed on the knowledge gained from some simpler instrument. If we follow the chain backwards through simpler instruments, it is difficult to find a beginning but it is there, though far back in history. A savage may employ a stick to test the depth of a stream before crossing it. This is a simple instrument used to predict whether the depth will bring the water to his knees or head. If we cut notches on the stick, and perhaps require the man holding it to pass an examination, it becomes a respectable scientific instrument, and converts the stick from a depthoscope to a depthmeter. We could forgive the savage if he regarded the notches as powerful magic signs; but the magic is powerful, for the notches provide a means by which the answer can be rapidly and concisely communicated to other human beings to guide their own future behaviour. We could trace the use of instruments still further back in animals that make use of objects as tools.

Many simple measuring instruments, the measuring rod, or the measure pressed down and

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overflowing go back to where the record is lost in the mists of time. One could describe Stonehenge as an early scientific instrument which indicated the occurrence of summer and winter solstice, and provided the practical arts of agriculture with guidance in the seasons and the time of planting, sowing and harvesting. It is clear that we must accept the remote and simple ancestry of scientific instruments. Their purpose is to extend the senses, and get over some of the errors of the unaided nervous system, and to code information for the use of other individuals.

The sensitivity of sense organs at any moment depends on what stimuli have acted on them recently and the only reliable quantitative answer man can give is, 'I cannot tell the difference between these'; the alternative, 'they differ in such a particular', can tell us nothing quantitative. All instruments have to reduce phenomena to a form in which they can be presented to an observer for this judgement—preferably a pointer in coincidence with a scale mark; alternatively counting of discrete and distinguishable events or objects to give numerical results.

Formal science in its full elaboration has not escaped from its simple basis in human nervous systems, though the consequences of this are often neglected.

Our senses provide us not with 'meters' but with 'scopes'. To say that one body feels twice as hot as another is meaningless except when we can learn to correlate subjective impressions with readings of external instruments. Our senses can often be led astray in many well-known illusions.

That our senses do not give information that we can easily communicate to each other by signs or symbols in a quantitative form does not mean that they are not capable of giving highly accurate information to the brain, and it may even be communicated to others in codings other than numerical hieroglyphs. The dance of the bees[7] that communicates direction and distance of a nectar source to other bees should make us cautious of underestimating primitive quantitative communication, and such methods transfer a neural relationship that could be called knowledge from one individual nervous system to another.

We have only to consider simple skills to realise that quantitatively accurate information is derived from the senses and used to guide action. For example, to throw assorted stones to hit a target requires not only accurate information of relative positions, but also the assessment of the mass of the stone to produce an accurately controlled sequence of muscular movements. As we learn more of the events in the nervous system that lie behind the accurate control of action, it is clear that the nervous system is able to abstract information from its senses in a quantitative form and use it to initiate accurately controlled movements. If we built a machine to throw assorted stones to hit a target, we should have to give it a mechanism that was based on our formal knowledge of Newton's Laws to do so. Can we then say that the thrower's neural mechanisms have abstracted Newton's laws in some private form for guidance of action in that nervous system—I think we must accept this implication—this abstraction cannot however be easily communicated but is locked in the nervous system in some form not so readily passed on to others.

We must, thus, distinguish two forms of analysis of the environment performed by brains or nervous systems. One a guide for private action and the basis of skill which one may call Neural Science and the other formal science which we can readily communicate by signs, symbols and experiments or demonstrations; this vast body of analysis we share with each other and our predecessors, and pass on to our successors. Through formal science the individual has access to a condensed product from millions of experiments and thousands of able brains.

The essence of experiment is to alter things and see what happens. This is true both for the private discoveries of neural science, and the discoveries of the relations of cause and effect which lead to formal science. In forming a new hypothesis, we must suppose data are placed in a new relationship by the brain, and this neural linking is then tested in experiment. If the predicted result follows, the hypothesis is then tested in other relations; if, however, the prediction fails the hypothesis is wrong and the neural relation has not been coded to represent the relation in the external world. Thus, from the relation between a deliberate alteration and a succeeding observation, the environment is found to be orderly in many particulars. There are two essential conditions for the

result of the alteration to be useful in prediction. A record of the alteration must be kept and a record of the result made for comparison. In formal science these records are of many kinds which can, in part, be reduced to hieroglyphs or numbers. In neural science the record is kept in the nervous system, and we are still groping to discover the form of this record. If the prior alteration or action is not recorded, the result loses its significance and prediction fails. This is well illustrated in tossing a penny by hand when we are unable to keep a sufficiently accurate record of the motor act imparting spin to the coin and so we are ignorant of how many rotations will occur, and so the result cannot be forecast or directed. The result can, however, be made certain if we use a sufficiently accurate penny tossing machine. The laws of chance are in fact the laws of human ignorance, and prediction depends on retaining a record of how a situation stands and of what alteration is applied to it. The greater the detail of these records the more precisely can the prediction be made. Statistical methods enable our ignorance to be segregated from our knowledge in a complex situation.

Formal science has arisen out of neural science but has not escaped all the peculiarities impressed on the latter by the properties of the senses and of the nervous systems or brains to which they are attached.

The development of instruments to aid the senses in analysis of the phenomena of the physical world has in the last 100 years gone full circle and many instruments have been turned back to analyse the nervous systems of man and animals; this has produced a great increase in knowledge of these, the most highly organised physical systems we know, which incidentally are continually being produced in enormous numbers by quite unskilled labour.

To turn to examination of what this instrumental study of the nervous system yields, I propose to outline our present views of the sensory actions of the nervous system.

The organs of sense are highly specialised structures, some for touch at the skin surface, others for chemical changes from substances on the tongue, which man interprets as taste, or mechanical displacement of structures in the inner ear produced by rapidly changing air pressure which we analyse as sounds, or photochemical changes in the retina of the eye which give the sense of sight: these and others all send information to the brain by way of nerve fibres. In man, between two and three million nerve fibres are responsible for transmitting the information from the various sense organs to the spinal cord and brain. As our President this year, Sir Wilfrid Le Gros Clark, has often emphasised in his writings, the sense organs of man resemble those of animals very closely. Man possesses no great superiority in his sense organs; some animals possess sense organs specialised in some particular direction so that they may be superior to our own, the eye of a hawk or the nose of a dog could be cited. But where man excels is in the central mechanisms for analysing and correlating the messages he receives from his senses.

The essential action of a nerve fibre is to conduct a change of state at one end along the fibre to another part. The wave of physico-chemical change which propagates along the nerve fibre is called the nerve impulse and is accompanied by small electrical changes which spread ahead of the nerve impulse to activate the regions towards which it then travels. The nature of nerve conduction has been clarified in its physical details during the last fifty years especially by work in Cambridge by Keith Lucas[15] and by Adrian,[1] and more recently by Hodgkin and Huxley.[10]

In large mammalian nerve fibres of 16–18 microns in diameter, conduction is at about 120 metres a second, but in smaller fibres activity travels more slowly and in fibres of one micron in diameter or less may be no more than 0·5 metres per second. Fibres of different sizes serve various functions in the nervous system. The activity in the nerve fibre consists of a brief self-terminating activity which leaves the fibre unable to conduct again for one or two milliseconds. The intensity of the impulse in any fibre is normally a fixed quantity however the impulse is initiated. As a signalling channel the fibre can be compared to a telegraph line carrying morse dots only up to some 500 per second. Information can only be transmitted in this form, but unlike the telegraph line the nerve fibre is a trigger device which provides its own electrical energy for propagation all along the line, the impulse does not become weaker as it travels. Moreover, it is a living cell of great length, it is

self repairing if damaged, and derives its energy from materials in the blood. Each peripheral nerve fibre behaves as a separate conductor practically independent of its neighbours.

Thus to our present knowledge, all information is conveyed to brains as trains of nerve impulses, which do not differ fundamentally in nature if they come from the eye, the ear or the skin, but arrive by separate channels with nerve fibres often grouped together as in the optic, auditory or spinal nerves.

The sensory nerve endings terminate in a variety of ways in sense organs, where specialised structures protect them from some of the physical and chemical events around them and raise their sensitivity to others. Thus the nerve endings of the retina within the eye are protected from mechanical disturbances but sensitised to light entering the eye by photochemical substances produced by specialised cells. They are, however, sensitive to mechanical disturbances as when the eyeball is pressed or struck when impulses reach the brain to be mistaken for those produced by light. Similar mistaken appreciations can occur from most sense organs. The exclusion of stimuli other than those to which the organ is specialised is not complete.

The analysis of the action of sense organs has been greatly extended by the advent of valve amplifiers which came into use in physiology about 1920. This has enabled the very small release of electrical energy by single nerve fibres to be used to indicate the presence of nerve impulses and so nerve messages can be tapped and recorded. Until 1930 the technical difficulties made progress slow, but the great development in electrical technique since then has made these techniques much easier to use and electronic amplifiers are as familiar as microscopes in many laboratories in which work on nerves is undertaken.

It has become clear that what we call electronic techniques have been anticipated by millions of years in nerve structures but the units concerned, nerve cells and fibres, make a transistorised calculator look a very crude instrument. The linking of studies of real and artificial brains aids our understanding of both and is a field of co-operation of a number of disciplines in many laboratories; it seems probable that discovery of the means by which nerve cells perform elaborate control functions so compactly and elegantly may well help to guide future invention in electronics.

When a sense organ is stimulated by an appropriate physical or chemical change such as pressure or a chemical irritant, the nerve impulses travelling in the sensory nerves can be recorded as electrical changes which indicate the nature of the activity going on. In the last thirty-five years many techniques have been developed for following the activity in single nerve fibres in animal experiments. In many sense organs it is found that a rhythmic series of impulses is set up in each unit and the repetition rate in the fibre is related to the intensity of stimulation. In the sense organ, at the nerve termination, it is found that the initiation of impulses is preceded by a local change which is accompanied by an electrical depolarisation produced at the end of the fibre which is known as a generator potential.[3, 11] In all sense organs so far studied, it appears that the stimulus energy is transferred to trigger nerve fibres via an electrical process; it must, however, be borne in mind that in aqueous media movement of ions has an electrical counterpart, but ions also have a chemical nature which may often be as important as the non-specific electrical charge. The sensory nerve terminations are thus a source of messages to the nervous system which may produce visible reflex effects, and in man result in conscious sensation. Impulses also produce effects in the central nervous system that are detected with more difficulty, but alter the reactions to later messages. I do not wish here to use the word memory for these short-lasting effects that can be followed in animals in some detail.

Large nerve fibres conduct rapidly, and where they occur the time delay between an event and the arrival of the nerve message at the central nervous system is not very great, but large nerve fibres appear to be a biological luxury, and if all nerve fibres were of the largest diameter, nerves would occupy many times the space they in fact do, and would become impossibly clumsy. By far the greatest number of the nerve fibres going to the nervous system have a small diameter and a slow conduction rate. Information conveyed by them will be greatly delayed in transit. Thus following a sudden change some fibres deliver their information within a few milliseconds while

others may require even seconds in a large animal before their information is delivered. Thus, there is early warning of events, followed by more information coming in later. It is interesting that many of the large fibres are occupied carrying information from muscles for the control of these same muscles, and adapting their effect to suit the load that is met; as any servo engineer knows, it is most desirable to reduce the delays in a feed back mechanism; in these simplest biological servo mechanisms the fastest conducting fibres known are used.

It perhaps comes as a slight shock to realise that everything reaching consciousness from the senses must relate to events that are already past in physical time, but this conclusion is inescapable. For example, at close range, the flash of a gun will be signalled from eye to brain so slowly that the bullet will strike that brain before the nerve impulses have reached it. Moreover, the delay differs for the various sensory pathways. The control that a brain exercises on external events is entirely dependent on predictor mechanisms that enable later events in a sequence to be anticipated to take action appropriate to meet them. The unconscious analysis of the environment that makes this possible is what I want to convey in the term neural science. This forms a basis of prediction to control external events of immediate concern to an animal, just as formal science provides man with a shared basis of prediction for such control on a wider front.

We must all realise the extraordinary accurate control of action that is manifest in many skills which require quantitatively accurate motor performance adjusted from sensory information. Thus a cricketer has to forecast the future position of a ball approaching him and the pattern of the stroke he delivers is determined, and leaves his brain many milliseconds before the ball reaches his bat to be sent neatly into a part of the field where a fielder cannot arrive in time to catch it. The structures by which this is achieved, living nerve cells, little aggregates of highly organised jelly built up of constantly changing atoms and molecules, do not appear to provide extreme stability of form, but manifestly ensure continuity of function. They appear to require, and are provided with, an extremely closely controlled environment, not only in Claude Bernard's sense of constancy of temperature and chemical surroundings, but also by extremely efficient protection from mechanical and other physical disturbances. They seem to have achieved functional stability in ways quite unlike those we adopt to produce stability in automatic computing devices. It is profitable to explore the nature of the precision of which they are capable, and how they come to possess group properties of high stability which do not require a uniformity of unit properties greater than those we observe, and how collectively they present us with phenomena, which at present we fail to be able to provide from the demonstrable properties of the units. But to return to the simpler aspects of the matter.

The sense organs are often regarded in a passive role as receivers of information, whereas in fact their very nature requires them to be used for active exploration of the environment in cooperation with the motor systems. As Adrian[1] pointed out over thirty years ago, we do not use our senses only as observing instruments—some of them could tell us very little if we did. But we use them actively in conjunction with our muscles. To take a simple example, to feel a golf ball might mean to be hit by one, though the common meaning would be that it is taken in the hands, turned round, squeezed and discovered to be hard, rough, round and so on. This active investigation is essentially 'alter things and see what happens', the essence of experiment, and it enables the nervous system to get round some of the limitations of the sense organs, particularly that of adaptation owing to which many sense organs do not respond to steady stimuli but actively changing the pressure and contact with the sense organs of the hands enables these to yield the maximum information. If the ball were placed in an immobile hand, very little would be learned about it. It would, I fear, take too long to discuss how the apparently passive senses of sight and hearing become fully useful and meaningful by association with other senses; the active exploration of the environment is essential for the senses to be fully used.

One of the more intriguing examples of motor testing of the environment to obtain information is that discovered forty years ago by Hartridge[9] when he showed that bats avoided obstacles in the dark, and suggested this was done by detecting the echo of their squeak to get a sound picture of

their surroundings. This sound echo location has since been investigated in detail particularly by Professor Griffin[8] and his collaborators at Harvard, who have shown the precision with which a bat locates and captures flying insects by this method. Under water mammals also appear to use high frequency sounds for the same purpose and porpoises[12] and dolphins have been investigated in recent years, and the former are found to be able to avoid invisible obstacles such as a perspex obstruction suddenly introduced into waters familiar to them. The blind man tapping with his stick is able to develop similar abilities which are latent in sighted persons but become highly developed in those accidentally blinded. The blind often use clickers on the heels of their shoes to produce a signal for echo location as they walk. The importance of wireless echoes in man-made radar has stimulated investigation of these parallel ways of obtaining information from a distance which must have been in use in biological systems long before man appeared on earth.

This testing of the environment by motor signals occurs in many sensory systems; it parallels experiment in formal science. Thus in feeling the golf ball, signals are sent to muscles to apply changing pressure and contact and the signals echoed to the sense organs of the hand from the golf ball are analysed. Similarly, but less obviously, testing is applied in the use of many other senses, such as moving the head to alter parallax to extract more information from the image falling on the retina.

The term 'exflex'[16] can be used to denote a motor act which is monitored by the nervous system and results in a return of sensory information from the environment. The continual waving of antennae in insects or crustaceans seeking contact stimuli shows such motor action. When contact occurs this exflex is followed by reflex responses, in which the order of sensory and motor components is reversed. Thus neural science derives not only from passive but also from active exploration of the environment—essentially experimentation.

In echo location very precise appreciation of the timing of echoes is required and it is found that the human brain is capable of distinguishing sounds that reach the two ears with time differences of the order of 10 millionths of a second, which is interpreted as the sound coming from the left or right of the subject. Possibly in the bat the discrimination may be much finer than this. In animals such as dogs and cats, the simple turning of the head towards a source of sound involves the analysis of such minute time differences in the messages from two ears to produce the accurate response that occurs.

The interaction of sensory impulses from two sources can be seen in a much simpler context in the spinal cord. Some twenty-five years ago Barron & Matthews[2] found that the discharges in secondary neurones could be initiated by stimulation of one part of the skin of a hind limb of a cat but could be inhibited by stimulating a different region and that if the inhibitory stimulus were applied first, that which previously produced an impulse discharge then failed to do so. Sensory pathways exhibit excitation and inhibition as in the better known reflex arc. In recent years many detailed studies of such phenomena, e.g. by Skoglund,[13] have shown that the primary sensory discharges entering the spinal cord interact on reaching secondary neurones. What goes forward towards the brain is not the simple incoming information, but derives from the relationship of different parts of a complex message. In this the time relations are an important, perhaps the paramount, factor. Simple incoming volleys of impulses cause demonstrable changes in neurones far and wide within the nervous system, e.g. Botelho & Matthews[4] found when a volley of impulses entered the spinal cord of a frog from any nerve chosen from all four limbs, changes occurred in the local excitability of any single fibre tested in the dorsal columns. The restriction of activity to highly specific channels in the central nervous system as seen in the simplest reflex pathways is an artificial simplification often deliberately fostered by using deep anaesthesia; normally many other pathways are active, but only those leading to motor neurones are made evident. It appears impossible for impulses to enter the central nervous system by one group of nerve fibres without altering the paths open to those arriving by thousands of others. The theories of the synapse were developed to meet the simplest cases: they still have to be fitted to cover the wide interaction found to occur among elements of the actual nervous system. The enormous

branching of fibres within the central nervous system clearly may be partly responsible for what is observed.

In simple neural systems—for example the reflex pathway of the knee jerk—we know from the work of Renshaw[17] and Lloyd[14] that a change in the timing of two volleys of nerve impulses of only half a thousandth of a second can make the difference between evoking a large muscular response or none at all. This depends on two volleys of nerve impulses from different peripheral sites reaching a certain point in the spinal cord namely the surface of the motor neurones within a narrow margin of time, and changes in their relative timing of fractions of a millisecond completely alter the resulting action.

In peripheral nerves, time occupied in conduction at first sight appears a biological disadvantage, but within the central nervous system it would appear to have important functions in providing what an electrical engineer calls delay circuits, each moreover under constant conditions of temperature, etc., will introduce a consistent change in timing. It has been suggested by Braitenberg[5] from the structure of the cerebellum that it could provide a biological stop watch.

The temporal resolution of events in the nervous system is very high indeed, and suggests a basis for much of the precision which it exhibits in the actions it produces.

If two nerve impulses travel through a group of secondary neurones in fibres running from different directions and giving branches to those neurones, the place where they will coincide at the surface of a secondary neurone and alter its state or cause it to become active, is determined by the *time* interval between them, just as the place of collision of trains leaving London and Norwich and travelling at steady speeds on a single track would be determined by the interval between their start. If the collision results in a fire the *locus* of this fire would be determined by the interval between the start of the trains. The locus of the fire will determine which fire brigades in the eastern counties receive messages to attend the fire, thus the relative timing of the starts results in many different responses, and this timing determines many different messages.

Returning to the neurones, it is clear that a vast number of different messages can be conveyed simply by changes in the relative timing of two nerve impulses, which will determine where they meet. If we take a rate of final conduction of 2 metres per second with a head-on approach at 4 metres per second, the point of coincidence will alter by 20 microns for every 5 microseconds change in timing of either. If we take 50 microns as the spacing between secondary neurones representing fire brigades along the railway line, we find that 2 impulses in two fibres entering such a system at intervals of 0–1 second, could convey 40,000 different messages. Or for 0–1/100 second can convey 400 different messages.

The limit to the number of different messages two impulses in two fibres can convey within a given time depends on the central resolution possible: we know for impulses from the ears this is very high. There is no reason to expect it to be much less for many other central analyses. If we extend this to three dimensions with a third impulse to coincide with that resulting from the first two coinciding, the number of different messages carried by the time relations of three impulses becomes an astronomical number. But enough has been said to show the great possibilities of signalling complex information residing in the time relations of impulses entering the C.N.S.

The pattern of central activity may thus be determined by the time relation of any pair of impulses, as well as by the fibres which are active.

It is perhaps not surprising that important mechanisms seem selectively to reduce the inflow of information to the brain and the restriction of attention is to a minute fraction of the whole.

The importance of timing in altering the information of two messages seen so clearly from the ears, also occurs with messages from the eyes. The messages from one eye can be made to occur late by placing a neutral filter over one eye which causes the impulses to be delayed in initiation within this eye, the binocular depth perception of moving objects is greatly disturbed and for instance a pendulum swinging in a straight line viewed obliquely appears to trace an ellipse. Clearly here relative timing of messages is of great significance.

It would seem probable that the delay of some of the impulses from the skin in small fibres may

be important in their central analysis. Recent work on the structures of the human skin particularly by Weddel[20] has disturbed the older views of punctate specific nerve endings, and some other characteristics such as timing of impulses would fit the facts as a basis of part of sensory quality in the message very well. From our knowledge of skin endings and their nerve fibres the proportion of fast and slow travelling impulses and their delay in initiation would be expected to vary with different modes of stimulation. Since the observations of Head & Rivers[18] we know that a deficit of some of the impulses from the skin after nerve injury, completely alters the quality of conscious sensation.

Only in its simplest manifestations can a nervous system be regarded as a wiring diagram of neurones. Very simple organisms do present a system of identifiable connections and stereotyped responses, and these are also found in the most elementary reflexes of higher animals, but here many other pathways are open to the nerve impulses which traverse them.

These connections of the elementary reflexes are not determined from the immediate environment, but only activated by it, but are none the less purposive, and complex reactions occur in which learning appears precluded. An example is the righting reflexes found in all animals—these are present at birth in some species.

As was pointed out above, purposive reactions anticipate changes in the environment and in reflexes carry mandatory instructions to action appropriate to an environment of which the organism may have no individual experience. The possession and transmission of these reflexes by the parents is a condition of the viability of offspring. An obvious example is the suckling reflex which appears in the foetus of many animals and is present long before it is necessary for the survival of the individual. Again the righting reflexes which are essential for an animal to have effective mechanical activities in an environment which is unsymmetrical owing to the presence of a gravitational field are present in some mammalian species at birth. The messages from the labyrinth are already mandatory.

The use of concepts in science such as reflex or gravity enable us to discuss with precision the known facts around these terms and can be used as full stops to our thinking beyond the regions where hypotheses can lead to profitable analysis, but with other advances of knowledge at some later stage they can sometimes clog the further development of ideas that may be valuable. For some reason the idea that animals resemble superior clockwork toys still persists in dismissing elements of behaviour as 'only' reflex, and neglecting the extraordinary facts concealed behind this word, for reflexes give evidence of basic predictor mechanisms enabling the animal to forestall events in the environment. The presence of normal reflexes is far more essential for survival than the external details of the animal. For example, an animal born with a deformed or absent leg has a good chance of survival, though less than the normal, but there is ample evidence that an animal or man born deficient in any of a number of visceral and protective reflexes has very little chance of survival.

The possiblity of organisms evading the simpler determinisms of their stable physical environment by fore knowledge of that environment is implicit in effective purposive reflexes. These appear a more important and subtle component of inheritance than the more easily studied external characteristics. The great advance in well controlled behavioural studies in recent years serves to underline the magnitude of the ignorance that we conceal behind the word 'reflex'.

The complexity of genetic instructions required to include elaborate patterns of inborn reflex connections would appear likely to tax the ingenuity of the inventors of molecular genetic theories in future when the details of reflex organisation come to be included in this field.

In man we can only partly separate inherited and learnt components, but it appears that the nervous system is given much of its basic neural science by inheritance which is brought up to date and extended by learning which blends its quota of experimental information to the whole. The nervous system appears to build up a neural science from infancy adding associations of action and sense data to the reflex data appropriate to the properties of matter found in the environment. A baby has already gone far in neural science when he finds that his rattle goes out of his control when dropped to the ground. Formal science is later grafted on to concepts conditioned by neural science, and takes over the space time analysis of

the latter, only to have to discard this later for Einstein's very different concept of space and time not completely independent of each other.

The final predictor mechanisms achieved enable the organism to survive in a changing environment and to live with its competing fellow or less well equipped organisms.

Thus neural science starts in associations of neurones that are genetically determined. To these exploration of the environment adds refinement, leading to the elaboration of individual skills. Shared formal science is developed from this in which communication between different nervous systems plays an essential role. The final product cannot eliminate all the limitations imposed by the physical mechanisms used, but can and does strive to reduce them. Increasing knowledge of nervous systems as communication channels can assist in recognising the nature of limitation to be expected.

Forty years ago Sir Arthur Eddington[6] wrote—'It is one thing for the human mind to extract from the phenomena of nature the laws which it has itself put into them; it may be a far harder thing to extract laws over which it has had no control.' The time is perhaps approaching when it might be suggested that the word brain could be substituted for mind in this statement, thus the proposition would be made one that could be moved from philosophy to the experimentally based sciences; and emphasises the essential unity of the sciences and the inter-relation of the working of the brain and the theories of matter man's brain has produced. When we find nervous systems are forced to handle information discontinuously, should we perhaps wonder whether our physical theories in which we are forced to introduce discontinuities in matter and energy to agree with observation, can be as independent of our nervous systems as we often think, particularly when we cannot make complete descriptions in terms of particles and must add wave properties not discrete in time. Are we perhaps discovering that the nervous system abhors a continuum?

There is great danger in the presentation of scientific material without due regard to its place in our systems of knowledge. This arises all too easily in elementary scientific teaching, or in popularisation of science. The beautiful models made to summarise data relating to the theory of molecular structure are often presented, especially since the advent of television, as though they were drawn as one can draw the railings outside the window to represent the shape of tangible objects. This is unimportant among scientists who understand the models to be coded diagrams and that the entities they are dealing with are dynamic, with moving charges and vibrating particles that have stabilities of pattern not only in space, but also in time, which can only be included by the assignment of frequencies and wave structure to them. But to the untutored mind they give an air of simple finality that is the negation of the spirit of science. We can see around us the spread of a popular pseudo-science that is regarded as a body of final dogma accepted almost as a religion, and perhaps welcomed in some quarters as providing a stronger popular opiate. But what Thomas Sprat in his *History of the Royal Society* in 1667 called 'the long and tedious doubting of the true philosophical spirit' which has produced the sciences as we know them is in danger of being hidden, and of being cramped by the pressure of mass demands for certainties. To quote Sprat again—'indeed this is an error which is very natural to mens minds, . . . they fixed and determined their judgements, on general conclusions too soon, and so could not afterwards alter them by any new appearances. . . . This is a temper of mind, of all others the most pernicious; to which I may chiefly attribute the slowness of the increase of knowledge amongst men.'

The most remarkable physical structures we know are those we use so casually and take for granted, and of which we really know so little. The frequent neglect of the fact that science is a product of man interacting with his environment through the medium of a nervous system has, I think, contributed on both sides to the many bitter controversies (some fought out in the British Association itself) between scientists perhaps oversimplifying their concepts, and churchmen defending dogmatic aspects of religion. Perhaps as our understanding grows of the nervous system as an instrument capable of prediction and so able to exercise control over the environment many of these arguments will appear as fruitless as the medieval schoolmen disputing the number of angels that could dance on the point of a needle.

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PHOTOGRAMMETRY AT YOUR SERVICE

By Colonel J. B. P. ANGWIN, M.B.E., F.R.I.C.S.

The old refrain, 'If you want to know the time, ask a policeman', might be rendered in contemporary terms, 'If you want to know the size . . . (or the shape or the place) . . . ask a photogrammetrist'. For there are few problems of determination of size or shape, volume or location, that may not be solved by means of photogrammetry.

Perhaps your own need to know any of these things is not immediately apparent, but whether you are an archaeologist or architect, ecologist or economist, engineer, forester, geologist, prospector, surgeon, town-planner or, indeed whatever, your interest in life may be, the chances are that photogrammetry is already serving you in some way or other and that it can serve you still more if you choose to ponder on it. There is also the chance that if you are in the running as an engineer or a mathematician or a scientist, or as one of several other things, you can be of service to photogrammetry. So you may take your pick, serve or be served.

For just over a century the process of photogrammetry, which uses photographs as permanent portable records for the purpose of making accurate measurements (at one's convenience), has been gradually but surely developing. The spur for development was the need for topographical surveys and it is to meet this expanding need that the process is mainly used today. However the general aim is to recapture and record, graphically or numerically, the measured relationships between objects in space, the three-dimensional relationships. In other words, permanent recording of '3D' for almost any purpose.

The origin of the word 'Photogrammetry' is a little obscure though its derivation is obvious enough. It probably came into use first about the time of the Franco-Prussian War although the fact that a photograph is a picture in which perspective can be measured was recognised thirty years earlier by the Frenchman Dominique François Jean Arago. By 1859, the embryo of the process as we know it today had been fathered by another Frenchman, an army engineer officer, Aimé Laussedat. Since then, the embryo has developed to maturity through the joint efforts of scientists of many nations.

Fig. 1.—Aerial photographing of overlapping strips of land. *(By courtesy of Hunting Surveys Ltd.)*

In its early days photogrammetry was confined to using photographs taken on the ground and, although ingenious attempts at aerial photography were made almost at the outset, little success was achieved until the second decade of this century when aeroplanes became reliable moving carriers of airborne gear and the designers of photogram-

metric apparatus set about designing special cameras to be carried in them. Since then the process of photogrammetry has become more and more integrated with the development of aircraft, and topographical photogrammetrists rely almost entirely on aerial photography for their raw material. Ground photography is, however, still used by exploring surveyors who probe for topographical knowledge on their feet and it is also increasingly used by non-topographical photogrammetrists for their own special purposes.

As a general rule in contemporary photogrammetry stereo-photographs are used and *photogrammetry* is often loosely used as though it were confined entirely to *stereo-photogrammetry*, which it is not, for single photographs do have their uses for measurement. For aerial surveys, areas to be mapped are usually covered by long, laterally overlapping, strips of separate photographs taken in sequence. The individual photographs in the sequence are taken at intervals of time so regulated (usually automatically) that every picture in the strip overlaps its precursor by 60 per cent. (Fig. 1). The time-intervals are regulated according to the speed and height of the aircraft relative to the ground, and the focal length of the camera. The fore-and-aft overlaps enable the photogrammetrist to reconstitute in his stereoscopic viewing apparatus a stereoscopic 'model' of the terrain from which accurate measurements can be made. In special-purpose photogrammetry, the photographs may be taken either with stereo-cameras or with simple cameras used from two or more appropriate viewpoints with the object of making measurements by intersection.

The Scope of Photogrammetry

The scope for photogrammetry is so vast that the International Society for Photogrammetry, founded some fifty years ago, is growing from strength to strength. Its ramifications over the fields of arts, sciences and technologies and its potential for service in practical affairs are indicated by the subjects discussed at the last Congress of the International Society which was held in London in September 1960. This was the ninth of a series that have been held every fourth year since 1913, with some interruptions, in one of the capital cities of the world. Subjects discussed included the following:

Quality of photographic image; survey navigation; infra-red photography; quality of stereovision; lens distortion; automation; standardisation of the expression of precision and error; radar altimetry, electronic computers, urban mapping; design of highways; nautical charting; railway design; problems of civil engineering, microscopy; ballistics; water-current measure; X-ray photogrammetry; analysis of road accident scenes; tropical vegetation and crops; sources of gravel; geological research; forestry; human ecology of the city; ice in the northern sea route. These are just some of the topics considered at the congress among some 770 persons from 69 different countries.

Naturally most of the participants in the congress were people engaged in the prosecution of photogrammetry in one way or another: some whose work is devoted to improving the process in its many facets, some concerned mainly with its applications in practical usages, some occupied with the design and manufacture of photogrammetric equipment and instruments, some dedicated to teaching, and some intrigued with the history. It is not proposed here to go deeply into these matters but simply to present a picture of the service that photogrammetry renders and can render to man with a spotlight on British contributions. Before doing this it is thought useful to give an outline of contemporary procedures and a glimpse of the future.

The Photogrammetric Process

The photogrammetric process as a whole falls into three broad interrelated phases, namely: (1) Planning the work; (2) Photography; (3) 'Plotting' (used here as a convenient though not exact omnibus term to cover all processes of setting up photographs for viewing and measurement, measuring them and recording the measurements in a readily appreciable form). These three phases apply to both topographical and non-topographical work but, in the latter, each kind of specialist work is likely to call for its own kind of special treatment within each phase. Only the procedures applicable generally within the phases of topographical work will be mentioned here.

In the first stages of planning, consultation is needed between the client who requires work done and the agency which is to carry it out, so as to

determine exactly what end-products (and maybe intermediary products too) will be needed to serve the client's purposes. Perhaps in the first instance speedily prepared rapid maps, uncontoured, or even photographic mosaics, will aid the client's own preliminary planning. Then the nature of the final maps needed—their scale or scales, the vertical intervals for contours, and the style and quantities required—must be decided. Relative costs of alternative schemes may have to be considered although of course there is the possibility that the client will know from past experience exactly what map-products he must have and will simply call for competitive tenders for them from different agencies.

Then, among important technical factors which the agency must consider in its own planning are the provisions of ground-control (and other ground work), and whether a single complete photographic coverage will suffice as the raw material for maps on, perhaps, several different scales. (A factor of enlargement of as much as 8× is regarded as allowable for photogrammetry using contemporary sensitized materials, cameras and precision plotting apparatus). Weather conditions are of great importance; for example in connection with a current survey of a large area in Nigeria for general development, it is noted that there have been great photographic difficulties in the past due to heavy layers of cloud for a large part of the year and dust-laden winds from the Sahara during much of the remainder. This is the sort of factor that may add much to the cost of a project and to the complexity of administrative arrangements. The administrative arrangements are in any event sufficiently complex in most major projects and depend much upon the goodwill of local authorities.

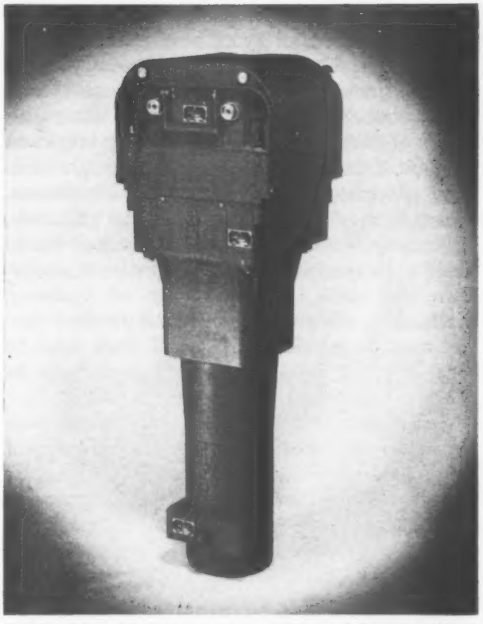

Fig. 2.—This is a Williamson type F.96 aerial camera fitted with a 48 in. lens and a 500 ft. magazine. It is the standard high altitude day reconnaissance camera of the R.A.F. *(Reproduced by courtesy of Williamson Manufacturing Co. Ltd.)*

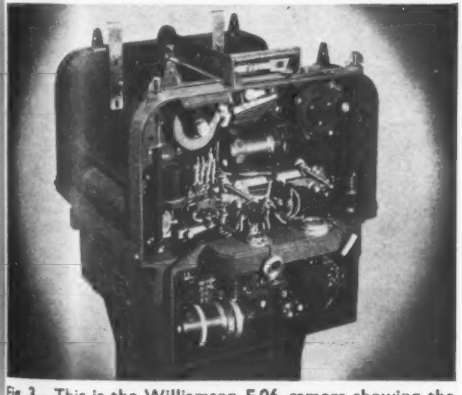

Fig. 3.—This is the Williamson F.96 camera showing the 500 ft. magazine and camera body with the cover removed. *(Reproduced by courtesy of Williamson Manufacturing Co. Ltd.*

Photography

In photographing an area the essentials are that the whole area should be covered in the most economical fashion, with no gaps, by stereoscopic photography of high quality at the required scale. Apart from consideration of weather, this requirement demands the provision of an aircraft capable of the necessary flight range and altitude, equipped with a camera of the appropriate specification using sensitized material of the utmost reliability and quality, and faultlessly navigated.

The scale of photography is governed by the flying height and the focal length of the camera, the formula being $s=\frac{h}{f}$

(For example, for a photographic scale of 1:10,000 using a 6-in. lens, a flying height of 5000 ft. is needed.) The focal lengths of contemporary survey cameras (including reconnaissance cameras) vary from about 3-in. to 48-in. and there is a multiplicity of designs (Figs. 2 & 3). Among important features of design (which has to be thought of in terms of measurement to 1 micron) are steadiness, preservation of optical flatness, shutter efficiency, uniformity of illumination and definition, means for effective synchronization, elimination of image-blur and static, and simplicity of operating mechanism, while temperature and pressure control must be provided. Above all there must be reliability, for one missed photograph may be nearly calamitous.

One notable and comparatively recent advance in camera design has been the introduction of super-wide-angle lenses with much greater angular covering power than in the past yet providing excellent resolution, brightness, and freedom from distortion (wide-angle, 75°–100°, super-wide-angle, 100°–120°). Another notable feature of contemporary design is the treatment of cameras and plotting apparatus as interdependent rather than independent items as in the past.

Sensitized photographic materials for photogrammetric negatives are sometimes on film base sometimes on glass. The relative merits are the subject of much discussion being bound up with questions of stability of dimension, weight, convenience of handling and cost. The emulsion must have particular qualities and considerable research is being directed to determine exactly what those qualities should be and how to define them in internationally standardised terms. For stereoscopic examination of the photography, positive prints must be taken from the negatives. Prints on paper serve for preliminary examination as well as for mosaics when required but for stereoscopic measurement positive transparencies on film or glass (diapositives) are needed. Ingenious 'dodging' printers which print by electronic scanning instead of simple contact or projection printing have been devised to improve the rendering of fine detail and further developments are expected in this direction.

The requirement for complete photographic coverage of an area, with no gaps, calls for very accurate navigation. In regions where reasonably good maps already exist, skilled photographic crews can achieve full cover by visual navigation but in poorly mapped areas special aids are needed. Some of the several aids available are described below. Actually aids to navigation may do more for the photogrammetrist than ensuring that there are no gaps in his photo coverage, because part of his work consists in reconstituting the position and orientation of the camera in space at the instant each exposure was made. Certain forms of aid to navigation help to save labour in this reconstitution process and current researches are being carried out to improve these aids so as to minimise the need for ground-control and complex processes of 'aerial triangulation'. Among these devices, the Airborne Profile Recorder (A.P.R.), recently invented in Canada, seems to have considerable possibilities. It has three chief components which are: (1) An accurate barometric recorder of changes of aircraft height relative to a starting datum (a statoscope); (2) a radar altimeter progressively recording heights of the aircraft above ground; and (3) a spotting camera. The A.P.R. was

Fig. 4.—This is a Williamson large-scale plotter type L.S.P. It is a graphical plotter of the anaglyph type. The platen on which the floating mark rests is on a small stand near the centre of the plotting table. *(Reproduced by courtesy of Williamson Manufacturing Co. Ltd.)*

devised for economical photography for linear surveys which require only a single strip of stereoscopic photography (for example, defined narrow lines of communication), as opposed to areal surveys, and its use as an aid to navigation is at present subsidiary to that sort of purpose.

Other widely used aids to navigation include systems of pulse radar (Shoran and Hiran) and radio phase comparison (Decca), which are dependent upon ground installations and may therefore not always be convenient. Doppler techniques, 'inertial guidance', and improvements in solar navigation are also being actively studied as aids both to navigation in flight and photogrammetric restitution of camera position and orientation.

Plotting

In stereo-photogrammetry results depend upon measurements of the apparent changes in positions of objects due to the changes in direction from which they are viewed (as in the apparent change in position of the background relative to a steady forefinger when viewed alternately with the right and left eye). These measurements of 'parallax' are got by one or the other of two different methods known respectively as the graphical or analogue method and the numerical or analytical method. Elementary stereoscopes with fairly simple auxiliary devices are still often used but over the past few decades photogrammetric instruments of great complexity have been evolved and are now widely used.

In these instruments the two stereo images are fused to disclose to the viewer a 'model' of the scene combined with a 'floating' mark which may be moved in the x, y and z dimensions by the operator using hand or foot controls so as to coincide with the apparent surface of the model at any desired point or to trace any feature apparent on it. In the Graphical method, the movements are communicated mechanically or electronically to a stylus drawing or scribing on a plot sheet. In the Numerical method, measurements of parallax of individual points are made with reference to a common selected datum point at the centre of the photograph and each measure is recorded for analytical treatment. There are two distinct types of Graphical plotting apparatus. In one type a monochrome model (with the floating mark) is viewed in the heart of the apparatus, in the other the model is projected as an anaglyph, on to a tablet or platen which carries a mark or point of light, and is viewed openly through bi-coloured spectacles. (Figs. 4 & 5.)

At least three-quarters of the land surfaces of the earth are as yet unmapped on reasonably adequate scales so that the field for topographical photogrammetry is immense and any means that can be found for increasing the pace of mapping by reducing waste of human effort and avoiding human errors in photogrammetry will benefit mankind. Recently there has been a breakthrough in automation by the design and development in Canada of an electronic scanning device applied to a standard graphical plotter of the anaglyph type. This embodies the ingenious rudiments of a replacement for the human eye in searching out elements of the stereoscopic model and for the

Fig. 5.—The British-made Thompson-Watts plotter Model 2 with front cover removed to reveal part of the internal mechanism. Designed particularly for large-scale mapping, though capable of handling small scales also with especial regard to speed of operation. *(Reproduced by courtesy of Hilger & Watts Ltd., London.)*

human brain in translating these elements to terms of measurement. Already this device has had significant successes in making assessments in the z (vertical) dimension and has been used for plotting contours and profiles with enhanced speed and saving of costs in highway design. The time has not yet arrived when, in the words of a distinguished photogrammetrist, one will be able to 'tell it (the apparatus) to design the most efficient highway from here to there, push the start button and go out to lunch' and return from lunch to find the job done. But a start has been made in one direction and is being made in others.

The design and manufacture of photogrammetric equipment and instruments is a highly competitive international business in which British manufacturers take a creditable part. Aerial cameras, stereoscopic plotting machines and accessories are made by Hilger & Watts Ltd., and Williamson Manufacturing Co. Ltd.; Stereoscopes and accessories by Barr & Stroud Ltd., C. F. Casella & Co. Ltd., and W. Ottway & Co. Ltd.; Navigational or distance measuring aids by Cooke Troughton & Simms Ltd., Decca Navigator Co. Ltd., Kelvin & Hughes Ltd., and Wallace & Tiernan Ltd.; 'Dodging' printers by E.M.I. and Rank Cintel Ltd., and Projectors by Grant Production Co. Ltd., while Wray (Optical) Works Ltd. make lenses. Fairey Air Surveys Ltd. have recently entered the camera-making field. The Ministry of Aviation, the Ordnance Survey, the Directorate of Military Survey, and the Directorate of Overseas Surveys themselves carry out investigations for the improvement of photogrammetric techniques and equipment and co-operate with the manufacturing firms in the development of new and improved apparatus.

Topographical Photogrammetry in Britain

The vast areas of the world that remain to be properly mapped, as well as those that require fresh mapping as developments take place, call for immense efforts in the realm of topographical photogrammetry. British organisations contribute much to these efforts.

In Britain itself, acknowledged universally to be already among the best mapped countries in the world, there is still room for photogrammetric work for particular mapping purposes. The Ordnance Survey is using photogrammetry for part of its programme of national mapping in urban areas for uncontoured plans on scale 1:1250 and in the programme of resurvey of mountain and moorland areas on scale 1:10,560 with contours at 25 ft. vertical intervals (the 'six-inch' map). This department has also used photography, including some experimental infra-red photography, of over 1000 miles of coastline in connection with tidal surveys. It has also been continuously developing techniques of analytical aerial triangulation, in which it was a pioneer, using the DEUCE electronic computer at the National Physical Laboratory and a computer from the Netherlands. Photography for the department is carried out under the Ministry of Aviation, navigation being by the Decca system. With exquisite fairness the department uses 13 British and 13 Continental plotting machines.

Apart from the national mapping programme there are many demands for special mapping by local authorities and other bodies, public and private, for such purposes as hydro-electric or housing and re-development schemes, and improvement of harbours and communications. These are undertaken on contract by one or other of the four British commercial concerns, either one of the two large companies Fairey Air Surveys Ltd., or Hunting Surveys Ltd., both of which also carry out much overseas work, or one of the two domestic operating firms, B.K.S. Air Surveys Ltd., or Meridian Airmaps Ltd.

Among the numerous works done by these companies recently, a few examples may be quoted. In 1960, the whole County of Essex was photographed from the air by Huntings on a scale about 1:10,560, mainly to obtain up-to-date information for County Development Plans based on the 6-inch Ordnance Survey maps. The photography can also be used for revision of town plans on larger scales. This company is now engaged on similar work for the whole of Kent, bar the Isle of Sheppey which was done in 1960. Copies of the photographs are available to local authorities or members of the public, on payment, on application to the County Councils concerned. In extension of aerial surveys of the Skelmersdale district done for the Lancashire County Council in 1959–60, Faireys have lately undertaken large scale survey and mapping for the Skelmersdale New Town project. They have also taken up aerial photography of most of Oxfordshire on scale 1:8,000 for the County Council. B.K.S.

recently carried out revision mapping of the Island of Jersey on a number of basic scales, and is currently making assessments of bulk excavations for contractors' costings. Meridian has made a large-scale survey of Southampton Docks intended mainly for a reorganization programme but used for a variety of purposes, and has undertaken surveys for trunk roads, power lines and railway modernisation.

Work Overseas

Those of us who are accustomed to the facility of being able to walk into the local stationers and buy a map that shows our own home and the way to reach it from the station or bus-terminal or to go from it by the shortest route to church or the 'local', may find it difficult to appreciate the crying need for maps of every sort in lands dotted all over the globe. Beyond the seas, the offshoots of British survey organisations and their affiliates reach out world-wide as participants of high repute in the work of meeting those needs. A catalogue of their work would be out of place here but some knowledge of it is surely a must.

The Directorate of Overseas Surveys, is the Government organisation concerned officially with surveys and mapping of British overseas territories. It works also in some independent territories such as Ghana and Nigeria. Work is being done in six territories of East and Central Africa, and four in West Africa as well as in North Borneo and a number of Pacific and West Indian islands. Scales are generally 1:50,000 in African territories and North Borneo, Sarawak and large islands such as Viti Levu in Fiji. Smaller scales are used in comparatively featureless areas while most of the Caribbean Islands are mapped on larger scales, as 1:25,000 to 1:10,000. Urgent requirements are usually met in the first instance by maps without contours followed by contoured maps or, in some regions, by maps with a system of hill-shading to provide preliminary information about relief. In addition to surveys for general development, the Directorate carries out special mapping for geological, forestry, and land-use purposes. Its work is financed partly from development and welfare funds and partly from money for technical assistance.

The Directorate of Military Surveys has carried out topographical photogrammetry on scales from 1:25,000 to 1:100,000 in Africa, the Arabian Peninsula and Malaya as well as plotting a test area in Canada using wide-angle photography and doing experimental work with a number of different instruments and techniques.

Fairey Air Surveys Ltd., and Hunting Surveys Ltd. both have headquarter offices in Britain. Between them they have associated or affiliated companies in Australia, Canada, India, New Zealand, Pakistan, the Rhodesias, and South America. Apart from many surveys for geological purposes the parent companies have done much work for general development or such special developments as irrigation, power, railways and roads or town planning, land-use and tenure, agriculture or forestry in at least twenty-three different territories. These include Afghanistan, British Guiana, Burma, Egypt, Hong Kong, the West Indies and many parts of Africa and the Near East. The areas surveyed have often covered many thousands of square miles, though quite small areas have frequently been done for special purposes. Typical variations are maps for general development of resources on scale 1:50,000 with contours at 20 m. or 20 ft., and maps for town-planning or industrial projects on scale 1:500 with contours at 1 or 2 ft. intervals.

Specialist (Non-Topographical) Photogrammetry

Non-topographical photogrammetry is rather a cumbrous term and among photogrammetrists there is some discussion as to its scope, but for purposes of this paper it is being taken as photogrammetry for special purposes not directly connected with measurements of the topography of the earth's land surfaces or the resources these afford for the economic use of men. These special applications cover an extremely wide range and it is not possible within a short compass to do more than outline the range and touch briefly on the details of some of them. In this it will be observed that some of the applications evidently fall within the domain of the expert photogrammetrist who, of his own volition, interests himself in some rather complex special application.

On the other hand it will be equally evident that there are already many special purposes, and might be many more, which are clearly the job of a specialist in some separate art, science, or technology, who recognises the possibilities of photo-

grammetry as a tool for his work and is thereby spurred to get a knowledge of its working principles and how to apply them to his special problems. This is not to say that the specialist need work out his problems alone, for it is sure that he will always be able to get the advice of an expert photogrammetrist if need be; it is merely to suggest that in certain sorts of work the specialist should take the initiative and hold it. In this connection it should be said that there are already clear signs of a demand for development of simplicity in equipment to suit specialist purposes which do not require the complex apparatus dear to the heart of the expert but forbidding to the tyro. The following outline of specialist works in photogrammetry does not pretend to be exhaustive. For convenience it is given more or less in alphabetical order.

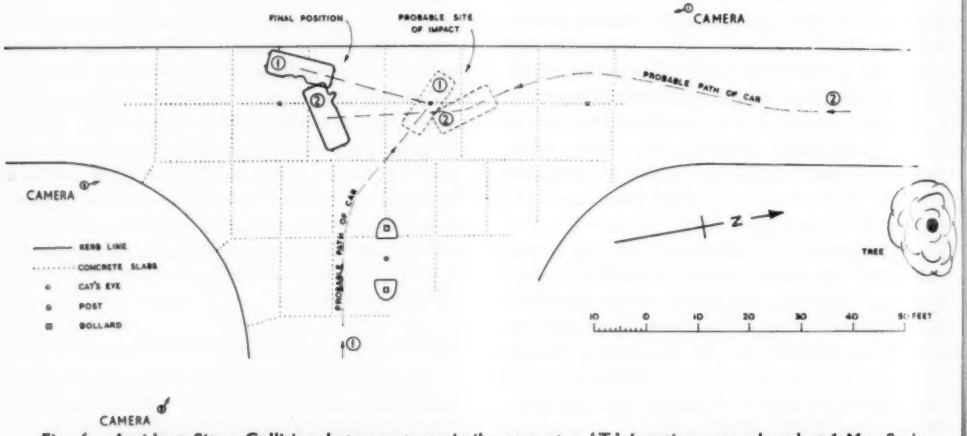

Fig. 6.—Accident Site: Collision between two similar cars at a 'T' junction reproduced at ¼ Map Scale. Map Scale 1:100 *(Crown copyright reserved. Reproduced by permission of the Controller of H.M. Stationery Office.)*

Animal husbandry has been the subject of experiment in the volumetric measurement of carcasses.

Anthropometric work has been done on skull measurements to determine racial characteristics in conditions when usual anthropometrical apparatus has failed to give results. It has also been used to collect anthropogeographical data in association with research into physiogeographic conditions in ancient settlements and irrigation and conservation projects.

Archaeology offers a fruitful field for the use of photogrammetry in the study of Roman roads and urban industrial centres and other works of ancient civilisations. Of especial current interest is the notable work now being done in Nubia on the desert shores of the Nile. Here for some five years past, a team has been making detailed records with the aid of photogrammetry of the great Abu Simbel group of monuments which will be submerged when the Nile waters are impounded by the new Aswan dam. This is a contribution to the history not only of the past but also of our own times which will be of significance far beyond the realms of the scientists directly concerned with the work.*

In *Architecture* photogrammetry is used for recording features of ancient buildings as an aid to preservation or restoration. Research is continuing into the positioning of photographic stations and provision of control data for this type of work which is closely linked with engineering.

Ballistic photogrammetry is in the forefront of contemporary specialist work. The general overall problem is to determine the space-time co-ordinates of high-speed sleds, aircraft, missiles and the like. A present work of magnitude in this field is a project for measurement of these data in respect of points on the orbit of a geodetic satellite,

* As we go to press it is learnt that an attempt will be made to preserve these monuments by a major engineering operation.

that is to say a satellite intended to aid in the solution of problems connected with the size and shape of the earth. This is a project in which cumulative progress may be foreseen because by determining better figures for the shape and size of the earth from measured orbits, more accurate restitutions of camera stations, and hence better measures of the satellite orbit, become possible. The process makes use of both stereo-photogrammetry and intersections from individual photographs taken from different viewpoints.

and profiles of piers while enlarging the navigability of the stream spanned. Another valuable use is the measurement of structural deformations under fluctuating loads.

Photogrammetry is used for various forms of *hydrometric* investigation such as the effects of varying currents on river bottoms which can be gauged by studying the effects of artificially generated currents on models. Similarly, measurements are made of wave patterns and other important dimensions in harbour models. An

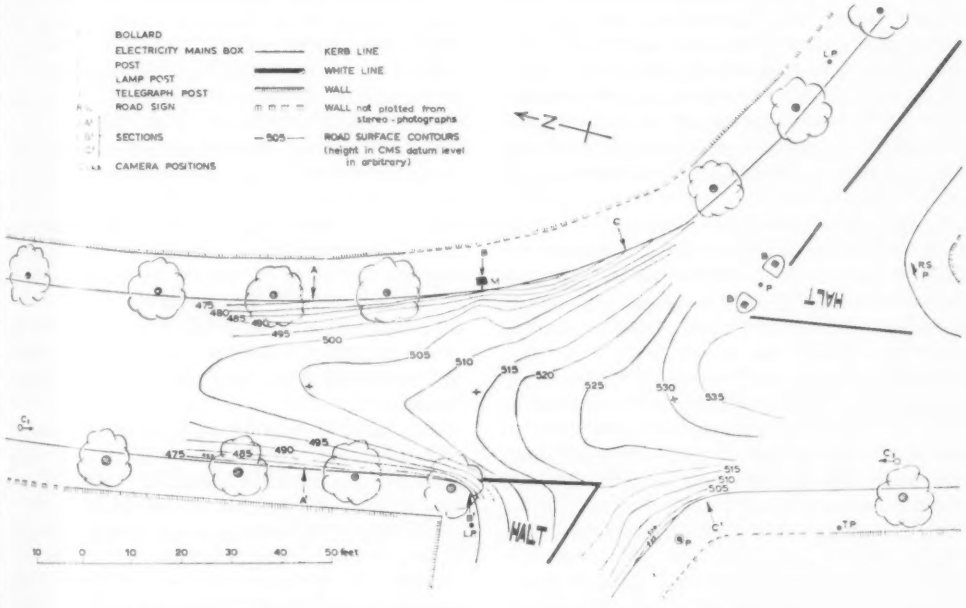

Fig. 7.—A Heavily Cambered Road. Reproduced at $\frac{1}{4}$ Map Scale. *(Crown copyright reserved. Reproduced by permission of the Controller of H.M. Stationery Office.)*

Corrosion, a menace difficult to combat, is best dealt with if its extent can be determined. Recent experiments have shown that this can be done by photogrammetry.

Engineering is a field to which topographical work contributes much but diverse specialist applications of photogrammetry are often used. For example it has been used to help in ensuring the retention of the character of design of an ancient bridge, its architectural structure, form of arches

interesting sideline on these is the use of permanganate to colour the water and of cork powder to bring out surface details for photography.

One special application being investigated in Britain is that of preparation directly by photogrammetry of working drawings of complex *industrial installations* from small-scale models built up and studied for ease of construction and operating efficiency. Another is concerned with the preparation of full-scale templates for building

motorcar bodies by direct plotting of photogrammetric measurements from approved models.

Meteorological data can be obtained by volumetric measurements of cloud formations, and the determination of wind-vectors by measuring photographs of smoke puffs or vapour trails.

Photogrammetry appears to have great potential value in the fields of *medical, surgical and veterinary* science particularly with X-ray photogrammetry. One advantage of the process in these fields is that it can be used to record details of changes in sensitive tissues without touching them.

The Moon: The photogrammetrist could scarcely escape being drawn into the vortex of outer space and recent studies have made great advances in knowledge of the face of the moon. The relative altitude of lunar features by measurement of shadows, previously done with great difficulty by micrometric means using small telescopes, is now being done from photographs and an ambitious gridded atlas of the moon is being prepared. Some experimental attempts are being made with stereo-photogrammetric measurements, but it is understood that these are unlikely to be successful until 'good measurable photographs have been obtained from space vehicles operating in its (the moon's) near vicinity'.

Finally, coming back to earth again, *traffic accidents*. A dictionary definition of an accident is: 'Event without apparent cause'. The operative word is 'apparent' and in many countries photogrammetry is being used experimentally to help in tracing the real causes. Ideally, for this purpose, the photogrammetrist should secure records in three dimensions of the scene of the accident, the road conditions that may have contributed to it and the resultant damage. This would perhaps be easy enough if the accident-prone motorist (or cyclist, or pedestrian) always had a photogrammetrist, with equipment at the ready, tagging along behind him, and if an accident could be curtained off, and if there were no other inconvenient impediments to photography. In the absence of such ideal conditions those who make investigations must be full of resource and ingenuity, and must be quick movers.

In Britain, investigations in this field are being made at the Road Research Laboratory of the Department of Scientific and Industrial Research. Two examples of their experimental work are illustrated. In the accident illustrated by the plan, Fig. 6, probable positions of the cars at impact were determined, despite numerous difficulties, from scrub marks of tyres on the road, debris and by 'fitting' the damaged outline of one car into that of the other. Fig. 7 depicts the photogrammetric plan of a fatal accident scene. This enabled camber curves to be plotted to throw light on possible causes of the accident.

It will be understood that it is no part of this work to attribute blame. It is done purely to obtain a record of facts that may have contributed to the accident.

So much for photogrammetry at your service. Its present range is wide; the breadth of scope for its expansion is almost illimitable. The boundaries of the photogrammetrist's vision are the paths of space-craft and the penetrations of Röntgen rays.

LIFE AND ENVIRONMENT ON THE BED OF THE SEA*

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A presidential address to this, or any other, Section of the British Association should, it seems to me, preferably be on a general topic and one which has long held the attention and exercised the curiosity of the speaker. I address you as a marine biologist of now, I realise, almost exactly 40 years standing and my topic—life and environment on the bed of the sea—could hardly be wider, covering, as it would seem to do, some two-thirds of the surface of the globe. But this becomes substantially reduced when I declare my interest confined to the relatively shallow bottom of the continental shelf, so omitting all mention of the members of the deep sea and abyssal faunas although there will inevitably be some reference to intertidal animals. This address will be concerned with some of the rich and varied population of invertebrates which can be sampled by dredge, trawl or grab and which inhabit every possible type of bottom in the shallow seas. For my examples I shall largely take animals which I have studied in life and as far as possible under conditions approximating to their natural habitat. It is the relation of the structure and habits of these animals to their environment which represents my major theme.

The floor of the continental shelf is a region of profound importance. There evolutionary changes have occurred which have stocked every available bottom environment. From it animals have migrated down the continental slope into the ever-increasing monotony and the ever-decreasing food supplies of the abyssal environment or upwards into the greater hazards, but richer returns, of shallower waters. This has sometimes led them on to the shore or into freshwaters and even, by one or other route, on to the land. In its vast resident populations it forms a major centre of secondary productivity. Especially in shallower depths these benthic animals feed directly on the phytoplankton carried down in turbulent water movements while everywhere a wealth of organic matter drops from above or falls out of suspension as water currents diminish. The members of this fauna, especially worms, molluscs and crustaceans, form the food of demersal fishes and so are of direct economic concern to mankind.

In these depths, nowhere exceeding some 100 fathoms and often less than half of this, the physical environment is not exacting. Salinity alters little if at all; temperature changes slowly and extremes are not great. Pressure, which may have some effect in greater depths has none here. What does vary, however, is the nature of the bottom. This is the reason why the content of dredge or trawl varies so much from place to place. Long before man began actually to view the bed of the sea by the aid of cameras or underwater television or, more recently, by gazing through the windows of a bathyscape upon a locally illuminated ocean floor, he had obtained a fair idea of the varied nature of the sea bed by the simple process of noting what adhered to the tallow inserted into the hollow at the end of the sounding lead.

The activities of Victorian naturalists and their contemporaries in western European countries revealed the wealth of animal life on the continental shelf. They provided the solid basis for our present knowledge of this fauna, indeed in many cases their books are still standard works of reference.

* Presidential Address delivered to Section D (Zoology) on August 31, 1961, at the Norwich Meeting of the British Association.

They noted differences due to type of bottom and to latitude and others due to depth although Edward Forbes' ideas of an azoic zone had to be abandoned when first H.M.S. *Lightning* and H.M.S. *Porcupine*, and later H.M.S. *Challenger*, found life at all depths to which they could send their rope-drawn trawls or dredges.

But all this was qualitative; it was left to the Danish naturalist, C. G. J. Petersen, before and after the First World War, by using the grab instead of the dredge or trawl, to begin the quantitative surveys of the sea bed which will always be associated with his name. His work in the North Sea revealed the presence on different types of bottom of a series of communities which he named after dominant or representative inhabitants. Uncertain about the precise status of such assemblages, he felt it 'best to regard the animals living on the sea bottom as communities, just as botanists group together the vegetation of the land into plant communities, even though in the present state of our knowledge it is impossible to show how intimate the mutual relations are between the animals of the sea in the single cases'. In addition, Petersen distinguished between the epifauna which lives upon a hard, and the infauna which lives within a soft, substrate. And although this breaks down when we consider animals which bore into a rocky substrate or which, like some scallops and the tropical windowpane shell (*Placuna*), live on the surface of soft substrates, it remains, as we shall see, a highly significant distinction.

In the hands of many successors, of whom his fellow countrymen Prof. R. Spärck and especially Prof. G. Thorson,[1] together with the late Mr. F. M. Davis[2] of the Lowestoft Laboratory, are the most outstanding, Petersen's work has been greatly extended although surprisingly little modified. We now know that the communities he identified are of world-wide distribution, varying sometimes no more than in the substitution of one species of a genus for another. Apart from the predator/prey relationship, there is little indication of interdependence between the members of a community. They represent groups of animals capable of living upon or within a certain type of substrate. Members of the epifauna feed in the most diverse manners; infaunal animals are necessarily more restricted. But to the extent that these bottom animals are suspension feeders they are essentially dependent on the primary producers, namely the phytoplankton of surface waters. On the other hand deposit feeders collect organic detritus the precise food value of which—whether it be nutritious in itself or only by virtue of the unicellular organisms which multiply within it—still largely eludes us. The presence of highly voracious carnivores has posed the question, how can new generations of their prey, settling usually from temporary life in the plankton above, establish themselves? Thorson[1] has shown how such settlement occurs when at least some of these predators are preoccupied by reproduction, when, for instance, the gonads of the ubiquitous brittle-stars are so enlarged that they are unable to feed.

A most notable contribution to our understanding of the maintenance of these bottom communities comes from the work of D. P. Wilson[3] at Plymouth. He has been the first conclusively to demonstrate that the planktonic stage which, except in polar seas, occurs in the life-history of the majority of bottom living invertebrates need not, on settlement, immediately metamorphose into the adult form and so demand the adult habitat. Where such larvae fall on to a substrate unsuitable for adult life they do not change. During a latent, but highly significant, period they may be carried about in bottom currents and so encounter a suitable substrate where some unknown factor stimulates change to the adult form. As recently further stressed by Scheltema[4] in his work on the whelk, *Nassarius obsoletus*, it appears that the presence of detrital (or bacterial) food rather than the physical nature of the substrata may provide the stimulus. In the settlement of epifaunal species there is the added factor of gregariousness, larvae settling most readily in the company of other members of the species.

The nature of the substrate depends on water movements: where these are greatest the bottom will be of scoured rock as in narrow channels or along the steep sides of fjords. Somewhat diminished movement allows the coarsest of gravel and shell fragments to settle but the smaller particles, first of sand and then of mud, will be carried further to be deposited in quieter water or in the stillness of deep pits, such as the Mallard Pit in Plymouth Sound. With decrease in particle size the proportion of organic matter increases, the

substrate coming to represent food as well as shelter. This applies more particularly to shallower water; with increasing depth, although the bottom is largely of mud below the level where surface movements affect it, the proportion of organic matter decreases.

Thus the bed of the continental shelf presents a series of environments due initially entirely to water movements, the source of the particles which compose the soft substrates being material carried down by rivers and torn by wave action from the shore. Such environments must have come into existence long before the evolution of living organisms able to exploit their possibilities and to add to these by formation of organic detritus derived from the breakdown of their bodies.

Viewing these environments as they may originally have been colonised we may regard the hard bottoms as being initially settled by epifaunal organisms which either attached themselves to it or crawled over it. But the infauna is clearly a secondary fauna. It is also a more restricted one. Thorson[1] estimates it as being only one-fourth as rich in species as the epifauna. He further notes that the latter is especially numerous in the tropics whereas the infauna—the better able by burrowing to escape the extremes of cold in shallow waters and intertidally—is about equally abundant in all latitudes. Burrowing in mud raises greater problems than in clean sand or gravel. While the organic matter present represents food it is also responsible for local lack of oxygen and so raises problems of respiration. Moreover the dense medium involves the formation of permanent burrows with consolidated walls into which a current of water for respiration and sometimes also for feeding, must be drawn. This involves elaborate structural and physiological adaptations.[5] So we may assume that this environment, however early it may have come into being, was colonised relatively late. This does not, however, imply that deposit feeders as such were necessarily preceded by suspension feeders in all Phyla. From an epifauna of most diverse feeding habits, the infauna is contrasted by being composed largely of suspension and deposit feeders. The former sieve their food from the water above, the latter collect it from the surface or just below this. There are also the predacious carnivores which come from the epifauna to invade soft substrates, moving effectively through this to seek out the sluggish, largely defenceless, members of the infauna.

Certainly over the course of evolutionary history all areas of the sea bottom have become closely settled as a result of a complex criss-cross of organic change and adaptation. To think, as we may reasonably do, in terms of existing animals, then the early evolved sponges and coelenterates are both almost entirely members of the epifauna. The former represent aggregations of choanoflagellates and retain the ancestral method of suspension feeding. The coelenterates probably alighted on the bottom after early evolution as pelagic animals being then, as now, carnivorous and securing their prey by tentacles armed with nematocysts. It is noteworthy that although these animals, in the form of a few sea anemones and cerianthids, have penetrated soft substrata, it is never as active predators. But as members of the epifauna they have had unparalleled success, most obviously in the case of the stony corals (Madreporaria) with powers of skeleton formation which have added vast areas of limestone to the surface of the globe. Moreover by virtue of the upward growth of reefs and their outward movement against the forces of wind and weather, these have come to provide a series of environments for life in which all manner of epifaunal animals, including species of corals themselves, have become adapted.

Subsequent evolution produced more active members of the epifauna—flatworms, nemertines, annelid worms and crustaceans—all of which crawled freely on their under surfaces or by means of appendages and were either carnivorous or omnivorous. Suspension feeders were represented by the early brachiopods. It was their misfortune that, partly through lack of motility, they failed successfully to colonise soft substrates. Some of the annelids took to infaunal life, as suspension feeders such as the sabellids, as deposit feeders such as *Arenicola* and as active predators such as *Nepthys*. A variety of largely omnivorous crustaceans accompanied them. The echinoderms were originally, and largely still remain, creatures of the epifauna although the great bulk of the attached Pelmatozoa are now extinct. Dependence on suctorial tube feet does involve dependence on a hard substratum. Nevertheless soft bottoms have been successfully invaded by modification of the tube feet in the starfish, *Astropecten*, by the

beautiful modification of spines and tube feet in the burrowing heart urchins so well described by Nichols,[6] by use of the arms in certain of the brittle-stars (Ophiuroids), and more general modification of the body in the mud-dwelling holothurians.

However, perhaps not unnaturally, it is on the Mollusca that I wish to concentrate attention. Here again we are on safe ground in regarding the primitive mollusc as an epifaunal animal, crawling as do so many of its modern ancestors on a hard substratum. In the form from which the great modern classes were all derived, it was, I think, a very simply constructed animal, certainly much simpler than the recently discovered *Neopilina*.[7] This could well represent survival, by migration into abyssal depths, of an early form before the Mollusca attained the secondary simplification which so probably represents the reason for their enormous subsequent success. Of the six existing classes, two (Monoplacophora and Polyplacophora) retain the original epifaunal habit; a third (Gastropoda) while still largely of this habit has exceptional evolutionary potential and includes infaunal (as well as pelagic and even parasitic) members; two others (Scaphopoda and Bivalvia) are essentially infaunal although members of the second have moved on to hard substrata and even back again. The last group (Cephalopoda) consists of essentially pelagic Mollusca and as such demands no attention here, although a few seek at least temporary refuge in sand.

First let us consider the Gastropoda. Here the viscero-pallium swung round in the horizontal plane to bring the mantle cavity in front so presenting both immediate problems and future possibilities to the newly emerged Class. These early Gastropoda were unaffected in immediate habit, remaining on a hard substratum where their nearest modern relatives, the Archaeogastropoda, live to this day. Indeed movement into a soft substratum was impossible so long as the forwardly directed mantle cavity continued to house gills, initially paired then reduced to one, so elaborate as easily to be fouled by incoming sediment. Today all such animals, the two gilled key-hole limpets (Fissurellidae) and the abolones or ormers (*Haliotis*) together with the numerous archaeogastropod limpets (Patellacea) and the great host of topshells (Trochacea), all extremely abundant under suitable conditions, occur almost exclusively on rocky shores.[8] They abound on coral reefs.

Change to the mesogastropod condition represented new arrangements in the reno-reproductive system which permitted invasion of freshwaters and even of the land but they also involved loss of the left row of filaments on the remaining gill and the attachment of this to the wall of the cavity from which the single row of filaments now projected. This major simplification by allowing sediment to pass easily through the cavity permitted these gastropods to live in more turbid waters. It also, incidentally, enabled them to become ciliary feeders and as a result even to become attached members of the epifauna such as the worm-like, cemented Vermetids and mesogastropod limpets such as *Crepidula* and *Capulus*. By means of ciliary (or in some Vermetids mucous) mechanisms, they exploit the possibilities of suspension feeding while attached to hard substrata.[9]

Passage into soft substrata is now also possible. An instructive example is supplied by a study of the 'hairy snail', *Trichotropis cancellatus* which I made during a recent visit to the Friday Harbor Laboratory of the University of Washington. This snail occurs in vast numbers on bottoms covered with accumulations of dead shells, i.e. where water movements are considerable. The animal, as noted by Graham[10] for an allied European species, is a ciliary feeder. But it is mobile, crawling readily when placed in an aquarium but always moving as high as possible and there becoming motionless, holding on with the mantle cavity open and feeding on such suspended matter as the water contains. In nature it lives on a very unstable substrate but can clearly re-establish itself, on the highest available place, when this is upset. Its great numbers indicate with what success it exploits the possibilities of life in this unusual environment.

With little more outward indication of a fundamental change in habit, the auger shell, *Turritella*,[11, 12] has fully exploited the possibilities of infaunal life. Species of this genus are abundant almost the world over on muddy gravel bottoms in medium depths. They burrow rapidly and then feed as do bivalves; the inhalant opening is fringed with sensory tentacles, the exhalant opening is prolonged into a siphon, unique amongst prosobranchs, which directs the water clear of the mud. Although

motile, the habit of life prevents copulation, sperm entering with the inhalent current.

Perhaps an even more surprising addition to the infauna comes from members of the superfamily Strombidae which includes the conchs and spider shells, species of *Strombus* and *Pterocera*[13] respectively, which lurch ponderously on tropical shores and shallow waters, usually on sandy bottoms into which the pointed operculum bites at each forward movement but into which owing to the size of the shell, they are in no danger of sinking. Allied to them are species of *Aporrhais*[14] in northern waters which burrow and then, with the proboscis, proceed to construct mucus-lined inhalant and exhalant openings so that a respiratory current can be maintained while the proboscis explores the substrate for food. Judging by their numbers hardly less successful than *Turritella*, these animals are pure deposit feeders the distribution of different species of *Aporrhais* being controlled by edaphic factors, *A. pes-pelecani* inhabiting muddy gravel while *A. serresiana* lives somewhat deeper on a bottom of softer mud. Neither can live in the typical habitat of the other although there is some overlap at the margin of these areas. The allied *Struthiolaria*[15] of southern waters has a similar burrowing habit but is a ciliary feeder.

The other infaunal mesogastropods are carnivores, notably the ubiquitous naticoids with smooth rounded shells of a great range of size and an enormous foot which carries them relentlessly through sandy substrates in pursuit largely of bivalves which they enter by means of a specially adapted proboscis. Reference should also be made to the many scavenging and carnivorous neogastropod whelks which plough over or through soft substrates with inhalant siphon projecting into the water above. Their allies, species of *Conus* and other toxiglossans, form the great epifaunal predators of warmer seas, actively attacking their prey with a long proboscis armed with a poison gland apparatus.

The Opisthobranchs are so various as to defy brief analysis. But, despite the fascinating range of feeding habits we associate with groups formerly known as tectibranchs and nudibranchs, they are largely members of the epifauna. The greatest migration from the basic habit is into the surface waters where both gymnosomatous and thecosomatous pteropods abound. Where they do enter soft substrata it is as carnivores, creatures such as *Scaphander* and *Philine* which, unlike the Naticoids, swallow their usually bivalve prey whole and then break it up in the gizzard. Finally to the extent that the pulmonates re-enter the sea, they do so as yet other groups of limpets and so as typical members of the scraping epifauna.

The Bivalvia are a Class in which the laterally compressed form renders penetration of a soft substratum easy while the enclosure, and final loss, of the head by the mantle/shell has, with certain peculiar exceptions, made them obligatory suspension or deposit feeders. Here are the supreme exploiters of infaunal life, well protected by the enclosing shell, active enough with the extensile foot, magnificently equipped by gills or oral appendages for feeding. With the movement of the inhalant opening posteriorly to lie beneath the exhalant opening the bivalves became capable of head foremost penetration of soft substrata to a depth only dependent on the length of the siphons to which the mantle margins were posteriorly extended. Nevertheless, as we shall see, this pre-eminently infaunal group produces highly efficient members of the epifauna which, in turn, gives rise to further inhabitants of the infauna.

It is inherently probable that the first bivalves were inhabitants of relatively 'clean' substrates into which, like the modern protobranch *Nucula*[16] and lamellibranch *Glycymeris*,[17] they burrowed superficially drawing in water anteriorly. Yet it remains questionable precisely how they fed. *Nucula* is undoubtedly the most primitive surviving bivalve but it is also a supremely successful genus with many species and these occurring in vast numbers. They inhabit, as Allen[18] has well shown in his survey of those inhabiting the Clyde Sea Area, a wide range of bottom condition from relatively clean sand to mud. All have small gills and long palp proboscides. The latter undoubtedly collect bottom deposits in large quantities: the former add some smaller quantity of suspended matter. In other words the most primitive living bivalve is a deposit feeder. While there is reason for thinking that the proboscides are not in themselves primitive structures, yet some mode of deposit feeding by means of the lips—which appears to be the case in *Neopilina*[7]—does appear a necessary intermediary stage before the gills had extended

far enough anteriorly and become large enough to take over sole responsibility for food collection.

With equal probability *Glycymeris*[17] may be considered the most primitive of existing suspension feeders. It occurs in shell gravel, a grade of substrate only a degree less coarse than that occupied by *Trichotropis*. It has no proboscides but fully developed filibranch gills and although the augmented inhalant current, now the sole source of food, is largely anterior this raises no problems because the substrate is so open. Without any deposition of organic particles, the environment is unsuited for a deposit feeder and too coarse for other suspension feeders. Consequently *Glycymeris* experiences singularly little competition.

With the passage of the inhalant opening to the posterior end—only partially achieved in *Glycymeris* and other members of the Arcacea[17]—all types of bottom become inhabited, most richly those brought into existence by swirling currents in relatively shallow water such as the Dogger Bank in the central southern North Sea. Water movements which collect sand particles also concentrate the phytoplankton which feeds the incalculable populations of *Spisula* and *Mactra*. These bivalves are examples of the supremely successful superfamily Mactracea members of which, such as the otter shell, *Lutraria*, and the great Pacific Horse-clam, *Schizothaerus*, develop long siphons and live permanently at depths of up to a foot below the surface. Such permanent vertical penetration demands efficient removal of the inevitable excess of material which enters with the inhalant stream.[19] Initially concentrated by ciliary currents into mucous-laden masses known as pseudofaeces this is periodically expelled from the inhalant chamber by way of the siphon or a separate ventral opening.

It is evidence of the supreme suitability of the bivalves for infaunal existence that such deep permanent penetration of the substrate has been achieved, independently of the mactrids, in three other groups of suspension feeders. In the Myacea, which contains representatives in a diversity of habitats, there are the well known 'gapers', *Mya arenaria* (the American soft-shelled clam) and *M. truncata*. Within the Saxicavacea is the common rock-boring genus *Hiatella* (*Saxicava*) but also the largest and deepest burrowing of all such bivalves, namely the geoduck, *Panope generosa*, of the north Pacific. Finally, in the Adesmacea, are the pholads[20] of which the least specialised members, such as the impressively large species of *Zirphaea*, burrow into stiff clay so doubtless indicating the manner in which their many more specialised relatives, such as the common piddock, *Pholas dactylus*, came to bore into rock. And this brings us to another meeting place of converging evolution because this capacity to bore into hard substrata, this infaunal occupation of what is essentially the epifaunal habitat, has also been achieved by many routes. A species of the Myacea, *Platyodon cancellatus*[21] and varied species of the venerid genus *Petricola*[22] have become rock borers by the same process. Conquest of this habitat from other directions is mentioned later.

Much of the adaptive capacity of bivalves is conditioned by the antecedent presence of structural features. Thus all deep burrowers (not necessarily borers) evolve from groups in which the siphons comprise all three folds of the mantle margins and so are encased in periostracum.[23] Too large to be withdrawn, these siphons could only be maintained if so protected. In other bivalves siphons may be composed solely of the inner, muscular fold of the mantle margin and be separate. These conditions of high mobility and siphonal independence have permitted evolution of the Tellinacea, a major group of lamellibranch bivalves specialised for deposit feeding.[24] Their numerous genera and species occupy a wide range of substrates. They penetrate into those of highest organic content where they collect detrital food by the groping action of the far-ranging inhalant siphon. This material is sorted on the extensive gills and palps and passed into the specialised, gizzard-like stomach. This applies particularly to the intertidal and shallow water species of *Tellina*, to the smaller *Abra* spp. of medium depths, to the larger, more rotund, species of *Macoma* which occur the world over and are characteristic of a certain type of bottom community, and to the much larger, very flattened *Scrobicularia* which inhabits the upper reaches of muddy inlets. This has naked inhalant siphons up to 6 in. long, yet both siphons can be completely withdrawn.[24]

Unlike the suspension feeders which may in places literally touch one another, the Tellinacea are spaced out, each with its feeding area.[25] They may also move horizontally to new feeding surfaces

as well as downward for protection. The large very flattened foot projects through so wide a pedal gape that connection between the valves at the base of the siphons has to be maintained by the special bracing of the cruciform muscle characteristic of this superfamily.[24]

Either as suspension or deposit feeders, the bivalves appear irrevocably committed to infaunal life. Only the grade of bottom material, or the presence or absence of adequate supplies of organic detritus, appear as limiting factors within the soft substrates they inhabit. But when the larval bivalve settles from the plankton to metamorphose into the adult form and assume the adult habit, it usually—and possibly invariably because we are ignorant of the late embryology of many species—possesses a byssus gland at the base of the recently formed foot. The secreted threads provide attachment during metamorphosis, to take the extreme case of *Teredo*, into a form capable of boring into wood. This post-larval organ, for so I would regard it, has been retained, by neoteny, into adult life. This permitted the exploitation of hard substrates we associate with the ubiquitous byssally attached mussels with many of the Arcas, with the pearl oysters (*Pinctada*) and many other typical members of the epifauna.

These three groups of byssally attached bivalves differ in the proportions of the body.[26] In *Arca* the shell is equilateral with anterior and posterior ends (and adductor muscles) of much the same size. In *Mytilus* the posterior end is enlarged at the expense of the anterior end while in the rounded pearl oysters the body has been re-organised around the solitary posterior adductor. This anterior reduction is one possible effect of byssal attachment;[26] in theory the posterior end could be similarly reduced but would restrict the size of the inhalant and exhalant openings. Enlargement of the posterior end had selective value because it has precisely opposite results. Loss of the anterior adductor is usually accompanied, as in the pearl oysters, by change to a horizontal posture after which the under valve (left in the true oysters (Ostraeidae) and right in others such as *Spondylus* or *Hinnites*)[27] may become cemented to the substrate. Or the byssus may migrate to the middle of the under surface and become calcified in the saddle oysters (Anomiidae). Membership of the attached epifauna is thus reinforced. But in certain cases the very nature of the bottom may be changed, effectively from an infaunal to an epifaunal habitat. Oysters may consolidate a soft substrate to form the massive reefs which once bordered hundreds of miles along the coasts of Europe and other continents until destroyed by over-exploitation. Similarly with their byssus threads mussels bind a muddy gravel surface so that it becomes an environment for an epifaunal community. Korringa[28] has described the varied fauna found on the shells of oysters.

Attachment in one form or other is not the only fate of these monomyarians. They may lose the byssus to become free and form the supremely successful group of the scallops, species of *Pecten*, *Chlamys*, or *Amussium*,[26] which, by sudden expulsions of water from the mantle cavity—a form of jet propulsion—their course directed by suitable disposition of the mantle margins, are able to execute a variety of swimming and escape movements. All of these activities represent incidental consequences of mechanisms concerned with cleansing of the mantle cavity.[29] Owing to their shape and mobility, species of scallops colonise the surface of soft substrates, for instance *Chlamys septemradiata*,[30] which lives always on the surface of muddy bottoms at some depth. From an infaunal life retention of the byssus thus led to invasion of hard substrates. By later loss of the byssus following major changes in form, freedom was regained and with it the capacity to live, horizontally disposed, on the surface of soft substrates in which remote ancestral forms once vertically burrowed.

Byssally attached heteromyarians may also, by a different route than the deep burrowers, become rock borers. They do so initially by means of the byssus which supplies attachment while they force their way into relatively soft rocks. Increased efficiency comes with greater elongation of the shell, the anterior end of which becomes secondarily enlarged by increase in the tangential component in shell growth. This is the case in *Botula*,[31] a mytiloid found in mud stones along the north Pacific coast of America. But in the somewhat more modified date mussel, *Lithophaga*,[31] byssal threads are few but secretion of acid assists boring which is confined to calcareous rocks, in which these animals may be immensely abundant. Next to wave action they, with other borers, are the most

potent agents in the destruction of coral rock and so responsible for major modification of the environment this represents.

Other heteromyarians have invaded soft substrates while retaining, indeed increasing, byssal secretion. These are the fan shells (Pinnidae)[32] in which the shell is greatly extended posteriorly, the animal living vertically embedded in substrates of sand, attaching itself to stones anything up to 2 ft. and more below the surface. Many adaptations are present. There is the means of rapid repair of the constantly damaged shell; there is a unique means of clearing broken shell out of the all-important exhalant cavity; there is remarkable secondary elongation of the ligament; there is a byssus of unrivalled length and abundance. Truly members of the infauna, it is no less certain that the fan shells are descended from members of the epifauna because only under the conditions of such an environment would the basic form be evolved which permitted this surprising re-entry into soft substrata of an immobile animal.

The diversity and ubiquity of living organisms is due primarily to the interplay of form and environment. Nowhere is this better displayed than on the ocean floor.

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POPULATION AND FOOD IN THE TROPICAL WORLD

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A dozen years ago Mr. Wendell Wilkie insisted that the world of our time is 'One World', so reduced in size by the development of communications and telecommunications that whatever takes place in any part of it is of vital concern to all the rest. Today this is a painfully evident truth; but it is just as true that in almost no other sense can the world be thought of as a unity. The ideological contrast between the Communist and Capitalist worlds is the division that springs first to all minds, but others no less fundamental have also to be reckoned with.

The separateness of the Oriental and Western worlds was emphasised by Halford Mackinder* 30 years ago, as the outstanding geographical result of the course of human history. He contrasted the occident, with about a third of the world's people living on both sides of the North Atlantic between the Volga and the Mississippi, and the Orient, with half the world's people in the monsoon lands of Asia, and both with the relative emptiness of the rest of the world where about a sixth of the total population are thinly spread over four-fifths of the land surface. He emphasised the stability of these great clusterings of humanity and the great excess in each of them of the annual internal increment of population, which he set at five millions in the occident and eight millions in the Orient, over the movements of people from either clustering to the other or to the rest of the world. This picture still remains a valid presentation of the essentials of world population distribution and emphasises a sociological division of humanity whose political implications we are only beginning to discover.

*H. J. Mackinder: 'The Human Habitat'. Presidential address to Section E (Geography) at the Centenary Meeting of the British Association, London, September 18, 1931.

Here it is my purpose, however, to lay emphasis on a division of the world no less fundamental and possibly in the long run, though it is no part of my purpose to consider the long run, even more significant. I refer to the Tropical World. It is a world foreign to us, one in which virtually all the material conditions of life are different from those we know. This difference is basically climatic: the tropics have been aptly described as the lands where winter never comes, and both nature and society in the tropical world are adapted to take advantage of this. European man, by contrast, has lived since palaeolithic times always under the compelling need to survive the winter; and in the major extensions of European society in Anglo-America and Soviet Asia that necessity has been in no way reduced.

Strictly speaking the tropical lands are those bounded polewards by the Tropics of Cancer and Capricorn, but for my present purpose the boundaries of the Tropical World must be political frontiers. So I include all the Americas except Anglo-America in the north and Chile, Argentina and Uruguay in the south. This takes in 16·8 sq. km. carrying (in 1955) some 155 million people. In Africa I exclude only the Atlas Lands in the north and the Union of South Africa in the south, but for good measure add the lands between the Red Sea and the Persian Gulf. Here, in the Afro-Arabian tropics, are a further 195 million people on 28 million sq. km. East of the Arabian sea are the lands of the oriental tropics from Pakistan to Formosa and the Philippines. The southern coastlands of China are also tropical and alone of the Chinese lands escape the rigours of winter—an exception of capital importance to the Chinese which, however, we must ignore here. As thus defined the oriental tropics are estimated to hold 668 million people on territories that total only

8·4 million sq. km. Finally in tropical Australia and the islands from New Guinea to Hawaii are another 4 million people on 1·5 million sq. km. In sum this makes (or rather *made* half a dozen years ago) 1020 million people on 54·6 million sq. km.—about 38 per cent of the world's population on 40 per cent of its land area. But the addition sum conceals the fact that figures are intended to reveal. Two-thirds of the people of the Tropical World live in the oriental tropics on only a sixth of the total area; the average population density is 80 per sq. km. The remaining third are spread over the 46 million sq. km. of the Latin American tropics, the Afro-Arabian tropics, and the Australo-Pacific tropics at densities that are respectively 9, 7 and 3 per sq. km. This contrast between the high population densities of the whole oriental tropics and the low densities of the other great divisions of the Tropical World is a fundamental fact in the human geography of the area.

We should note, however, that both high and low densities are associated with under-development as that term is currently used. It would obviously ill behove a European or a Russian or an American to say that the actual land of Java or Bengal was under-developed. The numbers of families that derive their livelihood from the soil of these lands is hardly comprehensible to Western minds. But the standards of living of these families are little better than those of the forest dwellers of Borneo or the Indians of Paraguay, and a world away from those we are accustomed to. Under-development refers to social, and especially economic organisation rather than to intensity of utilisation of land, and characterises all the countries of the Tropical World without exception, whether they be thickly or thinly peopled. Nor is under-development exclusive to the tropics, for all the countries of the orient except Japan must be so classified. Under-development is not a matter of either climate or population density. Rather is it a question of the stage reached in what before the war was called the population cycle but which today it is more fashionable to call the demographic transition. To this we must therefore now turn.

Death Control and the Demographic Transition

The demographic transition is an episode in the conditions of growth of a human population resulting from changes in its birth and death rates from an early state in which both are high to a final state in which both are low, through a transitional period in which first mortality and later fertility show marked reductions. Such a dry academic statement, however, gives no hint of the social revolution that may be involved. The early phase with fertility and mortality both high is well typified by eighteenth-century England, with a disease-ridden populace, an appalling infant mortality, a very high proportion of children in the population, and an expectation of life at birth of only about 20 years so that fewer than half the infants born ever became truly adult. During the nineteenth century improvements in diet, personal clothing and cleanliness, housing and sanitation, and the introduction of hospitals and public health measures effected great improvements in health conditions and reductions in mortality. The expectation of life rose—first in the upper and later in the lower classes—to 40 years or more. Since birth rates changed but little the excess of births over deaths increased from year to year and population grew increasingly rapidly. This is the second or early-expanding phase of the cycle.

In the third or late-expanding phase a decline of fertility sets in, as was the case in England from about 1870–80. To the factors responsible for reduced mortality, which we may collectively call death control, family limitation or birth control is added. The excess of births over deaths is progressively reduced, and increase of the total population continues at an ever slower rate. In the final phase, which 30 years ago it seemed that several European countries were approaching, the excess of births over deaths becomes so small that a stationary population ensues.

Now the tropical lands have long been known as lands of disease, and their peoples were until recently in the first phase of the cycle. High mortality and infant mortality, low expectation of life and an age structure with a heavy disproportion of infants, have been the rule in the twentieth century in the Tropical World as in eighteenth-century England, but where economic and social betterment of the people have been achieved with changes of diet, water supply and sanitary observance, striking improvements in health and expectation of life have followed. Such populations have already begun the transition. But in the last three decades a new factor has been at work. Medical

science now has the means and the techniques to make a direct attack upon disease. Antibiotics and sulphonamides save lives that were formerly lost: insecticides applied on a scale never before contemplated kill the insect vectors of some diseases and inoculation on a massive scale can confer virtual immunity upon whole populations. The advance of death control in the lands of disease has become dramatic and rapid. It may best be measured by increases in the expectation of life, and three maps that I have constructed on the basis of information contained in recent issues of the United Nations Demographic Year Book will allow us to consider these increases geographically.

Fig. 1 shows the expectation of life of males at birth for the year 1920. On it lines are drawn to enclose areas where the expectation of life exceeded a given value, much as isobars are drawn on a daily weather map. It will be seen that the highest values (more than 55 years) are confined to two areas, north-west Europe and eastern North America on the one hand, and Australia, New Zealand and white South Africa on the other. Away from these two areas the values fall off sharply, showing that outside them death control was still inoperative. Throughout the Tropical World it was less than 40 years, and over large areas probably much less as figures of 24 for India, 27 for Mexico and 33 for British Guiana forcibly suggest.

Our second map (Fig. 2) displays the state of affairs about 1950 and reveals what great changes had been wrought in 30 years. In the lands where death control had been effective at the earlier period medical science had reinforced the benefits of public health and given the people an expectation of roughly ten more years of life. The line for 65 years in 1950 runs much the same course as that for 55 years in 1920 and encloses a 70-year line round the Scandinavian countries. Values in excess of 50 years have spread widely over the Mediterranean and eastern Europe, and through Soviet Asia to link with those of Japan and many Pacific islands. Per contra the area where the expectation was still less than 40 years had contracted greatly: on practically all the margins of the Tropical World decisive improvements are manifest: death control is advancing into the lands of disease. Yet there remain vast areas in southern Asia and Africa and some in Latin America, where the improvements are still small in comparison with what is possible, and in them striking reductions in mortality must surely be expected in the next two decades.

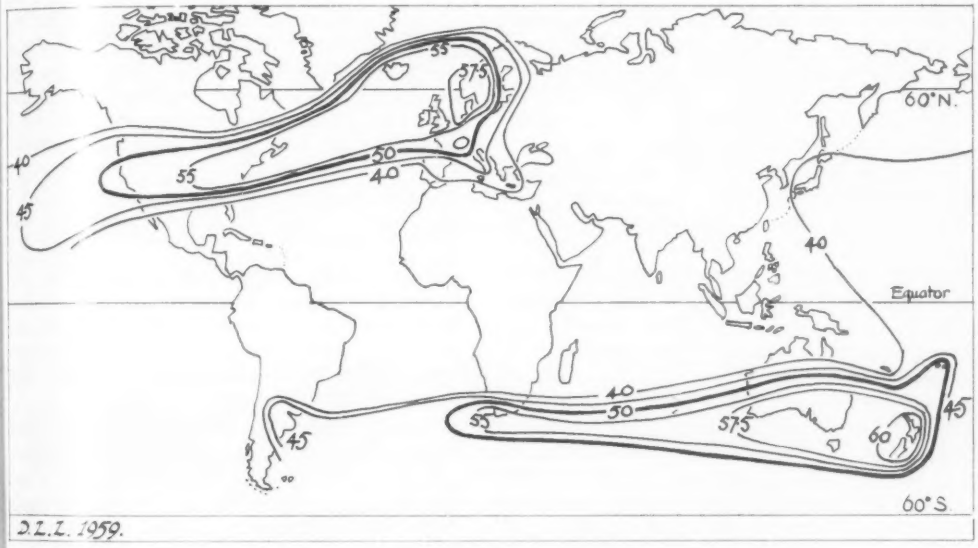

Fig. 1.—Expectation of life for males at birth about the year 1920.

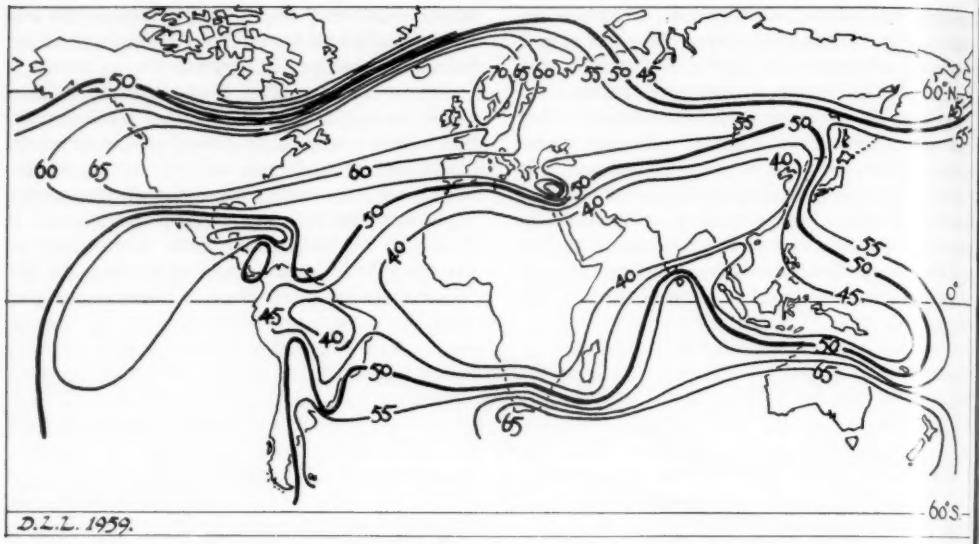

Fig. 2.—Expectation of life for males at birth about the year 1950.

The third map (Fig. 3) can be regarded as a map of the progress of death control in the twentieth century. Only in the Scandinavian countries and among the predominantly young populations of Australia and New Zealand was the expectation of life for males at birth as high as 50 years when the century opened. By plotting the date when it first attained that value in other countries and drawing isochronic lines for each decade we may see very clearly how the attainment of this degree of death control spread outwards from Scandinavia westwards across western Europe and the Atlantic to Anglo-America and the islands of the Pacific and the Caribbean, eastwards into central Asia and south-eastwards across the Mediterranean to Palestine. From the second region of early high expectation in Australia and New Zealand it spread to Tonga in 1929, Samoa by 1942 and Ceylon by 1947. In South America death control first became effective in the River Plate lands and next in the high, cool plateau of Bolivia. Elsewhere in the continent our selected value had just been reached about 1950 in the major cities, but doubtless still falls short of it throughout the interior lands.

In this pattern we may recognise something of far reaching significance for the Tropical World. It is not too fanciful to speak of death control having gained several 'bridgeheads' on the seaboard of tropical South America, and it seems likely that the area controlled to a similar degree may well expand from these bridgeheads to cover all but the empty interior of the continent by 1970. In monsoon Asia similar bridgeheads exist in Ceylon, Thailand and the Philippines and from them control may be expected to extend even more widely. Indeed, if the military metaphor of the bridgehead may be extended, it is possible that a major 'break-through' has already occurred. The recently reported total of 438 millions for the population of the Republic of India enumerated at the census earlier this year is greatly in excess of all anticipations (including the current five-year plan) and, what is more important, 75 millions in excess of the 1951 population. The figures imply a rate of growth not less than 2 per cent per annum over the decade. It has been assumed by the United Nations Statistical Office for some years that the rate of population growth in India was decidedly less than the world average, but the new evidence means that India's growth rate is decidedly higher than the world average, and indeed higher than that of any major territory outside the Tropical World for which data are available.

Within the Tropical World, however, such rates

of increase are common and in some populations substantially exceeded. Crude birth rates are available for 62 out of 118 territories in the Tropical World and with a few exceptions* the figures returned are moderately or very high. The arithmetic mean for all 62 is 34·8 per cent and the mode 37. For 20 territories the rates are between 40 and 48 per cent and for one it is 55 per cent. With declining death rates these figures mean high and increasing rates of natural increase over much or most of the Tropical World. In the middle American region from Mexico to British Guiana the rate of natural increase generally exceeds 30 per cent and similar rates are found in the Sudan, in some islands and territories of south-east Asia and some Pacific islands. These rates can be described differently as compound interest applied at 3 per cent per annum, a rate which leads to a doubling of capital in as little as 24 years. The rate we have possibly got to reckon with for India means doubling in 30 years and that for the Tropical World as a whole in 35 years. These are rates of growth that were never reached in England and Wales even during the height of the industrial and commercial expansion of the early nineteenth century, and the question naturally arises, how, and for how long, can they possibly be sustained in the tropics today. England's expanding population was fed by an agricultural revolution at home and the power to import food from abroad. Can either of these conditions be matched in the Tropical World today? England's expansion was a matter of adding ten millions to a ten million population in half a century. Some tropical countries are faced with increments much greater than this. Egypt and Nigeria each add half a million to their populations every year: Java, Mexico and Pakistan add more than a million apiece: and India, on present showing, may add 10 millions annually. For all these bodies food must be provided: for all these souls the satisfactions of a worthwhile life—at the very least some form of education and employment. Both in rate and magnitude the problems of the Tropical World

*Angola, Mozambique and Spanish Guinea have rates that have fluctuated about 13, 8 and 10 respectively over the last 10 years while Nyasaland and Paraguay have rates (respectively 9 and 13) which in the same time have declined sharply from values more than twice the present ones.

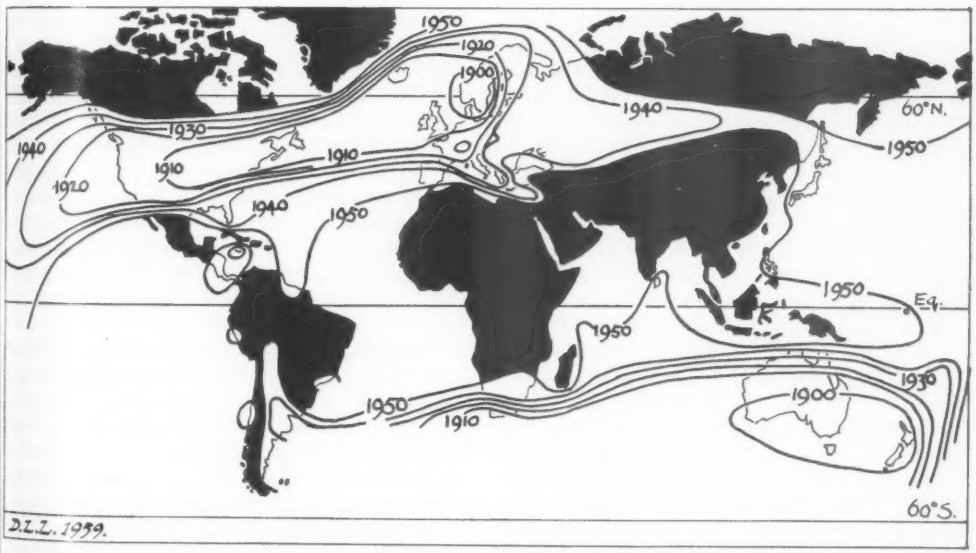

Fig. 3.—Progress of death control, 1900–1950. Isochronic lines at 10-year intervals indicate the decades in which the expectation of life for males at birth first exceeded 50 years.

today seem more severe than those of nineteenth-century England. How they will be solved I cannot say: but unless they are solved all talk of rising standards of living is vain self-deception. What it falls to a geographer to do is to emphasise the framework of the physical and social environment within which solutions must be sought.

Solutions to the Food/Population Equation

Such solutions can take one of two forms. They may aim either at providing greater food supplies or at minimising population growth by some sort of migration or by birth control. Migration, however, as will appear to some extent in the sequel, never achieves more than a temporary alleviation of population pressure. And in the form it most commonly assumes in the Tropical World today, namely of migration from the countryside into the urban centres and especially into the very large cities, it creates problems of under-employment and unemployment, of overcrowding and homelessness, of squalid and insanitary slums and shanty towns, of vice and immorality, lack of child care and education, that have everywhere outstripped the means, and frequently also the will, to solution. As to birth control one can say only this. However fervently one may hope, as I certainly do, that ways and means may be found appropriate and acceptable to the peoples of the tropical countries, whereby they may be able to achieve family limitation, one must accept the unpalatable facts that no such means are yet to hand, and that even if they were they could have little influence on the course of events during the next two decades at least. A day may come when migration, coupled, as it must be if it is to be in the least effective, with stringent family limitation in the areas from which the emigrants depart, may serve to reduce population pressure in lands in which it is most acute. The terraced slopes of the volcanoes of Java, the alluvial plains of East and West Bengal, the overcrowded sugar islands of the Indian Ocean or the Caribbean, or the green ribbon threaded by the Nile in Egypt, come at once to mind as cases in point, though for the most part the populations involved have as little will to migrate as they have knowledge of family limitation. Popular education has a long road to travel before migration and family limitation can combine, as they should, to relieve population pressures. And there are real risks that the process of education may be grimly hastened in one or other of these areas by experience of famine, epidemic disease, widespread misery and premature death.

Migration and birth control may be for tomorrow: for today the provision of greater food supplies is imperative, and for the achievement of that end three ways are open. First is the development of means that make possible the importation of food, second the extension of the areas at present under cultivation, and third the more intensive use of that area. Of the first two can say little for the problems involved are essentially economic. Import of food into the Tropical World from the countries that have surpluses of essential foods is perhaps the most limited of all the expedients available. In times and places of famine and distress food may be provided as charity or aid, but for the rest it must be paid for by exportable produce. A few tropical countries are the fortunate possessors of mineral resources that enable them to do just that—the oil of Venezuela and the Persian Gulf territories, and the tin of Malaya, Bolivia and Nigeria, are perhaps the most obvious examples. Others can grow commerical crops, the trees from which we derive our great beverages tea, coffee and cocoa; cane for sugar; the plants that yield the fibres cotton and sisal, or oil palms and ground nuts to provide industrial oils. All these are important to one territory or another. But by and large they must be in competition with food crops for space on which to be grown, and unless—as is the case with the very high-priced Egyptian cotton—the crop will permit the purchase of more food than could have been grown on the acreage devoted to it, or will permit the purchase of fertilisers and machinery to increase production on the remaining ground, cash crops will not offer a lasting solution of the difficulties.

Extensions to the cultivated area on the other hand may offer permanent additions to food and employment resources, though most of them can be achieved only by the diversion of capital and technical effort into fields where they may be slow to fructify. There is no lack of empty land in the tropics. From a careful examination of the largest scale maps available to me I have concluded that of all the land between the thirtieth parallels of north and south latitude (a rather larger area than

our Tropical World) 76 per cent is unoccupied—that is, without any inhabited place significant enough to have a name. Much of this empty land is arid desert, some of it is equatorial forest under a climate so wet that primitive peoples, denied the use of fire by the climate, have never been able to clear it, and commercial man has found it impossible to exploit without an indigenous labour supply. These extreme conditions at once lay emphasis on the paramount importance of water in the tropics. In the arid tropics all extensions of cultivation must await supplies of irrigation water for which large scale engineering and much capital are needed—capital that, as in the case of the High Dam of the Nile, is not always easy to obtain. In the wet tropics cultivation is possible only with elaborate water control and drainage, an art that has been carried to a high pitch in monsoon Asia, but has so far made little progress in the wet lands of Amazonia. Between the perennially wet and the perpetually arid tropics are the lands that are alternately drenched and parched—the lands of rainland cultivation. Towards the deserts the dry season becomes increasingly prolonged and the rainfall of the wet season increasingly unreliable from one year to another, so that on both counts rainfalls of 30 to 40 in., such as we are accustomed to in the lush green West Midland counties, may be quite inadequate, and under such conditions cultivation perforce gives place to a sort of pasturage. Extensions of cultivation are no doubt possible in many areas but 'dry farming' or conservation practices are not enough and widespread supplies of irrigation water must be provided either from perennial canals, or, as has been so successful in the plains of India in the last decade, from tube wells. And, if we are to avoid a repetition of the disgrace of Kongwa, no major extension of cultivation should be made before adequate climatological information is available. Indeed I cannot over-emphasise this point—water is vital to the life of the tropics, and in the face of this, our ignorance of the regional variations in the hydrological cycle is surely to be characterised as culpable neglect. Only in rare instances so far have governments appreciated that an understanding of the water resources of the tropics is a major key—probably *the* major key—to future progress.

Yet even when plans for the colonisation of empty lands have been wisely made and are based upon adequate quantitative investigations of the climatic environment and the hydrological situation, and even when no major engineering schemes are involved the capital costs of well-drilling and water supply, irrigation and drainage, are very high in relation to the number of colonists concerned. Moreover, since, in addition to food crops, cash crops must be grown to meet these costs, the means of collection, transportation and marketing must be created, thereby increasing costs per capita still more. Small wonder, then, that the venture newly embarked upon by the Government of Pakistan in planting settlers from overcrowded Bengal in an area of virgin desert, never before irrigated, a score or so miles east of the Indus delta and some sixty miles south of the Lower Sind barrage at Hyderabad, is confined to a mere 350 families. Or that an official publication of the republic of Colombia bluntly states that 'el aumento del área de explotación tiene los graves inconvenientes del alto costo de las colonizaciones, con los innumerables gastos en las instalaciones de viviendas, caminos, etc.'

Since neither importation of foodstuffs nor extensions of the cultivated area can do more than offer local solutions to favoured territories with export surpluses or able to attract capital, we must examine the prospects of large scale increases in the output of food crops from the ground already in cultivation. Such increases depend on the interactions of three strongly contrasted sets of conditions. In the first place there are the environmental conditions, which mean essentially water and soil: secondly there are the social conditions concerned with the traditional modes of life and husbandry of the native peoples: and thirdly there is the knowledge of theory and practice that modern science can make available. That this last could double—and eventually treble and quadruple—food production in most of the less developed countries is the considered conclusion of Dr. H. L. Richardson* of I.C.I. Ltd. and I see no reason to dissent from his view. Quite impressive evidence of what can be done by proper seed selection, improved cultivation methods, pest and disease control, and especially by the application of fertilisers,

* H. L. Richardson: 'What fertilisers could do to increase world food production', *The Advancement of Science*, Vol. **XVII**, pp. 472–80.

has already been provided by experiments carried out in the tropical countries themselves. The knowledge is undoubtedly there: the question is rather how can means be found of applying it within the framework of existing native societies that are well-adjusted to local environmental conditions.

Among the environmental conditions none is so important as the nature of the soil, and among the social conditions the mode of husbandry practised by the people, and the two are by no means unrelated. To these therefore we must give a little attention.

Tropical Husbandry and the Maintenance of Soil Fertility

It is most unfortunate that interest in, and exploitation of, tropical soils began many decades before their scientific study on the ground had led to any proper appreciation of what are their essential and what their accidental characteristics. In consequence much was said and written that in the light of latter-day knowledge can only be called nonsense, and highly erroneous notions have gained wide currency and even popularity. In the enthusiasm of the first days of discovery 'the primeval forest with its majestic trees' was taken as 'evidence of a young and virgin soil'. Closer acquaintance revealed some soils that were strongly leached and infertile, others that were rendered intractable because of concretionary deposits in the sub-soil or even appearing at the surface, and yet others that were washed away by the rains before the eyes of the chagrined planters, and a mood of despair and disillusionment followed. Many of these views were given extended currency by Pierre Gourou in the highly emotional chapter on soils which mars his otherwise sane and stimulating book, *Les Pays Tropicaux*. But the work of the last two decades, particularly by French and Belgian pedologists in Africa, now permits a more rational appraisal of the situation.

From this work I would draw three conclusions that are very relevant to our present discussion. First, that tropical soils show just as much variation in character and fertility as do the soils of extra-tropical regions. Secondly, that all tropical soils, being produced under conditions of continuous high temperature, naturally differ from those that sustain the agriculture of the developed countries, in the sense that the chemical and physical processes of pedogenesis are more thorough. Mature soil profiles in the tropics may have depths measured in as many feet as some European profiles have inches, and are commonly comprised mostly of unweatherable or highly weathered ingredients. In the extreme case in the perennially wet tropics soils may occur that are completely exhausted of their plant nutrients throughout a layer extending many feet below the surface. Thirdly, that in a state of nature under forest cover in the wet tropics such fertility as fully developed soils possess is concentrated almost entirely in the humic horizon close to the surface. It is this last circumstance that justifies those French writers who have spoken of the 'fragility' of tropical soils. This precious surface layer is indeed fragile and if the equilibrium between forest and soil is disturbed, as it must be by clearing the forest, then chemical changes lead to the loss of valuable plant nutrients; physical changes in the structure of the soil follow its desiccation and exposure to the sun, and in appropriate places to one of the opposed evils of progressive induration of the soil or subsoil by precipitated iron oxides, or of progressive loss of the surface layers by erosion.

The importance of these soil characteristics becomes manifest when we consider the two modes of husbandry which are most widely practised in the Tropical World—namely shifting cultivation in the forest, and rainland cultivation with fallowing in areas that have been cleared of their original woody or grassy cover. Shifting cultivation involves stripping the foliage from the trees and cutlassing the undergrowth of a patch of forest, burning the breast high litter (with the consequent destruction of anything up to 400 tons of organic matter per acre), planting a number of crops (yams, rice, maize, millet, cassava, bananas and vegetables) in association and succession to yield for two or three seasons before declining fertility and the invasion of weeds lead to the abandonment of the patch and the selection of a new one in some other piece of well-grown forest. A family may move its field and dwelling through a limited area of forest for a generation before returning to re-cultivate an old patch. From this description it will be seen that the precious humic layer of the forest soil is virtually never laid bare, and during the period of regrowth of the forest its structure and

fertility are regenerated. The system is thus one that may be continued in perpetuity, but imposes an obvious limitation on the number of families that can live in this way in a given area of forest. There is an upper limit of density to populations supported by shifting cultivation that is clearly indicated by the average population densities in persons per square kilometre of the following territories:

British Honduras	3	Madagascar	8
Nicaragua	8	Laos	6
Gabon	1	Sarawak	5
The Congo	5	New Guinea	3

The limit is certainly not above 10 persons per square kilometre. What this means will be realised when I say that among British counties only Sutherland (3) and Ross and Cromarty (8) have densities that are as low. When pressure of population increases, or if forest land is alienated in plantations or reserves, the reaction is to shorten the 30 or 40-year period of forest regeneration, not infrequently to 10 years or less. Then, in the words of the pedologist Duchaufour, 'the soil structure is degraded, the humus disappears and the soil climate is changed progressively in the sense of increased desiccation in the dry season: regressive evolution is thus begun and is aggravated by every succeeding return to cultivation'. There is reason to think that this situation is already of widespread occurrence.

The second mode of husbandry characteristic of the tropical lands—that of rainy season cultivation for one or two years followed by a period of fallow—differs from the first in being sedentary. Habitations are fixed, and though the cropped plots rotate through an area that area is itself circumscribed and fixed. In the course of the cycle of cultivation and fallow every part of it will be cropped, and from this springs the other great point of difference: under cultivation with fallowing the forest is never allowed to regenerate. In some areas the fallows are long, up to 6 or 8 years, in some they are short: in some wetter areas the fallow ground is covered by a dense woody or bushy growth; in drier areas the fallows are grassy. At best, with long woody fallows, there is some regeneration of the organic layer of the soil, but since the forest has gone irreparably there can be no replenishment of the mineral nutrients drawn up from the deepseated layer of active weathering by deep-rooted trees. Nevertheless by careful attention to the fallow growth, which may even consist of planted shrubs, and by mixtures, successions and rotations of crops discovered by experience and hallowed by tradition, a good deal may be made of the soils. Pressure of population leads to shortening of the duration of fallow, and on better soils this has been done with moderate success. Vines reports an instance where careful management of planted bush-fallows in the Ibo country of Nigeria has allowed a cycle of 18 months' cultivation followed by only 4 years fallow to be continued for over 40 years with 'relatively satisfactory maintenance of yields'. However, in poorer soils in the same area he reports that 'the farmers only found it possible to grow one crop of cassava after seven years of dense woody-fallow growth'.

The population densities that can be supported by such cultivation vary with the length of the cycle of cultivation and fallow from a lower limit of 20 or 30 to the sq. km., which is comparable to that of our own relatively empty counties like Berwickshire or Westmorland, up to densities that may be as high as 150 to the sq. km., which is much higher than any rural densities found in this country. At such high densities holdings are very minute and signs of overcrowding are not wanting. But in point of fact even higher densities are known to occur in India, in east Java and Madura (400 per sq. km.), in parts of Nigeria, and probably elsewhere. In all such cases the system shows signs of breaking down, and, as Gourou has suggested, such high densities in Nigeria can hardly be other than recent phenomena. Some land around the houses is continuously cropped and an attempt is made to maintain its fertility with human and household wastes, but the remainder suffers. Vines has described districts in the Ibo county of Nigeria where population densities are believed to attain 400 per sq. km.; he describes how, away from the 'compound land' near the houses, one may see 'an irregular mosaic of poor patches of crops and land under fallow' with much grass and bracken invading what should be bushy fallows, and much ground covered only by a creeping *Selaginella*. He notes that the area is not self-supporting in food, and Harrison Church, in discussing the same districts, speaks of alleviation by temporary migration or by renting farms in other parts of the

country. It is worth quoting Vines' conclusion: 'The soils after many years of cropping can only be described as *infertile* [sic]. However, since the rate of loss of humus is not great and most of the soil is unlikely to suffer much from erosion . . . it appears that the use of fertilisers in suitable rotations should maintain fairly good crop yields; the practical possibility of this depends largely on the relation between the cost of imported fertiliser, the local price of foodstuffs, and the organisation of production to enable the fertiliser to be paid for from the proceeds of the export of oil palm produce and possibly other commodities.' *Verbum sapienti.*

My picture of tropical husbandry would be left very unbalanced if I made no mention of the industrious cultivation which supports the teeming millions of Egypt, Java, the plains of Hindustan, the delta lands of Indo-China or the high intermont basins of Mexico. Here humanity has discovered and learned to utilise the most fertile soils of the Tropical World. But on those soils man has multiplied his numbers to the point where the same problems that we have just been considering all reappear, but at a greatly enhanced level of population density. Densities are commonly 200 to 400 per sq. km.—that is densities comparable to those of the mining and industrial counties of England: and in extreme instances they may exceed 1000 per sq. km., which is a figure comparable to that for Lancashire including Manchester, Liverpool and all its lesser industrial towns. At these high pressures of population, of course, two and sometimes three crops are taken from the same land each year, but signs of overpopulation are manifest in the acute subdivision of holdings, the endemic rural unemployment and under-employment, and, in certain cases where it is locally possible, by outward migration, especially of the males. A striking instance of such migration is that of more than half a million Bengalis, mostly from the district of Mymensingh into Assam in the present century. But the important thing to note is that despite the large numbers involved this migration is to be looked upon only as a symptom and not as a remedy. During the period in which it was most active (1911 to 1931) the density of population of the district of Mymensingh rose by 13 per cent from 280 to 317 per sq. km. and, in the words of Kingsley Davis, the migration simply 'promises to bring to the new territories conditions virtually identical with those from which the migrants have fled'.

If, in conclusion, we consider the Tropical World as a whole two points need to be emphasised. The first of these concerns fertilisers. It must be remembered that for far the greatest part tropical husbandry is carried on without either manures or fertilisers and that—with some important exceptions of which Egypt is the most conspicuous—the methods of maintaining the yields of temperate soils that have been evolved in Europe or China have no place in the tropics. Of the three great modes of husbandry shifting cultivation secures low but perennial crop yields from a given territory by effecting only the minimum disturbance in the natural equilibrium between soil and forest. Yields in such areas can only be raised by substituting some entirely different mode of husbandry. Floodland cultivation of rice secures high and perennial yields by cropping soils that are either inherently fertile or have their fertility renewed by annual flooding. And in the lands of alternating wet and dry seasons with cultivation in the rains, soil fertility has certainly been reduced by continuous cultivation, though the reduction is offset as far as possible by fallowing. The soils are certainly no worse than the soils of temperate Europe would be if treated in the same way—indeed, because of the rapidity with which plant residues break down in the tropics and vital nutrients are mobilised in the soil, the practice of fallowing is more effective than it would be in Europe. Herein obviously lies hope: what has been done in Europe can be done in the tropics. It is not desirable, as some agriculturalists thought a generation ago, to substitute European style crop rotations and cultivation practices for those of the tropics, but it is very necessary to find ways of bringing to tropical husbandry the benefits of scientific knowledge and especially of appropriate fertilisers. The average yield of wheat per acre in Pakistan today is no more than that of England in the fifteenth century and only a quarter of the modern yield. That it can certainly be raised is dramatically shown by the way in which the average wheat yield of Mexico—the most advanced of all the tropical countries—has been doubled in the last ten years. The staple food grain of Mexico, however, is maize not wheat and here the National Maize Commission created

in 1947 is undertaking an agricultural revolution. Regional centres supply hybrid maize for seed, specify cultivation techniques and necessary fertilisers, and already the national harvest is three times what it was twenty years ago. Even in the lands of intensive rice cultivation the possibilities of deriving more food from the soil are far from exhausted. The average yield of rice per acre in India today is no more than the yield in Japan nine or ten centuries ago, and only a quarter of the current Japanese yield. Small wonder that the suggestion has recently been made that the best form that Western aid to India could take might be the building of forty or more regionally distributed fertiliser plants.

The other general point concerns population pressure. We have seen that overpopulation is not confined to the areas having numerically the highest population densities. Regions of shifting cultivation are probably overpopulated at 10 persons per sq. km., and we have at present no body of experience of any system that could be successfully substituted for it to relieve such overpopulation in wet forest environments. Plantation agriculture may supplant it locally and absorb surplus labour, but an evolutionary solution to the problem is still to seek. Lands of rainland cultivation may become overpopulated at a variety of levels of density from 100 to 200 or even 400 persons per sq. km. according to the fertility of the soil and the efficacy of the cultivation and fallowing practices followed. But the spread of death control increases the pressure on all such areas and leads to too intensive a use of the soil and progressive deterioration of its productivity. The paddy fields of the oriental tropics may sustain even the highest of these population densities with ease—if the unremitting toil of so many bodies may be called ease: but over large areas population presses very heavily on the means of subsistence and cannot support further increases without risk of gross under-nourishment, loss of working capacity, and increased liability to endemic or epidemic disease. Thus at all levels of population density and in all parts of the tropics areas of over-population exist and may be expected to become more numerous.

Time, we say, waits for no man: but today in the Tropical World man's reproductive capacities outstrip time. Time moves at uniform pace with equal steps: population increase, quickened by death control, moves with accelerating tempo. China has attempted to resolve the dilemma of adjusting social change to the pace of population increase by 'the great leap forward' of social revolution. Can evolutionary processes based on serious study of the environmental, economic and social problems involved meet the predicament in which the countries of the Tropical World are already beginning to find themselves? To that question surely we, the physical and social scientists of the Western world, can give only one answer. And so, sooner or later, but the sooner the better, we must address ourselves wholeheartedly to the problems involved.

LOOKING AT science

Visual Aids for Mathematics Teaching

The Education Department of Associated Electrical Industries (Manchester) Ltd. (previously Metropolitan–Vickers Co. Ltd.) have recently published a very interesting booklet entitled 'Visual Aids'. This is intended to assist teachers of mathematics in industry and in technical colleges, and provides detailed information on the design and use of a whole series of models which can readily be constructed by the workshops of a college or training department. These are intended to help students understand simple arithmetical, algebraical and geometrical relationships of a kind required by most people in industry. They will be particularly useful for those in the craft grades of employment. Contents of the booklet are based on information provided by Siemens & Halske Works School in Berlin and are as follows:

Three angles of a triangle are equal to two right angles
Angle subtended by a diameter of a circle is a right angle
Teaching of ratios
Pythagoras' theorem
Algebraic expressions
Circumference of a circle
Area of a circle
Guldinus' theorem
Volume of a pyramid
Volume of a frustrum of a pyramid
Ratio of volumes of a cone, sphere and cylinder
Calculation of weights of castings
Principles of mechanics
Drawing an ellipse
Drawing exercise
Helix angle of a screw thread
Tool rake angles
Inspecting components for true shape.

Each demonstration model is chosen to demonstrate effectively one point and this may tend to restrict its use. An important exception is the illustration of the calculation of the weight of castings—a device which could find a variety of applications.

In view of the concern today about methods of mathematics teaching, a publication of this kind is to be welcomed, since it offers one approach to imaginative visual illustration.

If A.E.I. contemplate a further edition of this booklet, they would be well advised to change the present title, which is far too general in character, and might easily be overlooked by mathematics teachers.

Copies of the booklet and further details may be obtained from: The Education Department, Associated Electrical Industries (Manchester) Ltd., Trafford Park, Manchester.

Engineering Slides

The Institution of Civil Engineers has produced a 1961 Edition of their Slide Library Catalogue. This provides details of slides on a wide range of subjects including aerial photographic mapping lecture; anti-mosquito methods; coast erosion; electricity grid system; flood control; locomotives; refuse disposal; tramways; water supply, and very many others.

Well over 2000 slides are included in the library. These are available to members of the Institute and organisations or lecturers interested in the work of professional engineers. The slides are available on free loan, the borrower paying the return postage. They should be ordered at least 14 days in advance of the date required. Copies of the catalogue may be obtained from: The Institution of Civil Engineers, Great George Street, London, S.W.1.

CATALOGUE OF WALLCHARTS

Revised and enlarged Edition, January, 1961

THE EDUCATIONAL FOUNDATION FOR VISUAL AIDS,

33 QUEEN ANNE STREET, LONDON, W.1

The aim of this new edition of the E.F.V.A. Catalogue of Wallcharts is 'to provide one combined list of charts suitable for use in schools, so that teachers, education authorities, and others may have to hand a concise reference to all the charts available on any particular topic'.

It was decided to include in the catalogue all charts of specific teaching value designed especially for wall display at least 10 in. × 15 in. in size. Charts issued by commercial firms as advertising matter are included so long as they have teaching value and are not solely advertisements.

This very comprehensive list of charts includes twelve pages of material on science, six pages on health and hygiene, a page on agricultural science, twelve pages on industrial processes, and four pages on domestic science. In addition there is material on physical and economic geography, and regional geography, some of which will be of interest to the scientist.

The level of the material varies from 'Aids to Arithmetic', designed for primary school children, to 'Human Anatomy and Physiology', a series designed by Sir William Turner, Professor of Anatomy, University of Edinburgh.

Providing, as it does, details of many hundreds of charts from over one hundred different sources, this is an important work of reference for those who wish to use this form of visual presentation for teaching. Whilst the purpose of this catalogue is to cater for the needs of school-teachers, many of the charts would be valuable in other fields of education.

The catalogue is available, price 2*s.* 6*d.*, direct from the Educational Foundation for Visual Aids, 33 Queen Anne Street, London, W.1.

BOOKS

The Language of Mathematics. By Dr. F. W. Land. (John Murray, 1961) 264 pp. 21*s*. net.

This is a delightful book which will be read with pleasure by those who have a sound working knowledge of mathematics, and with profit by those whose competence is below O-level. The text conveys the enthusiasm which the author feels for the subject to which he has devoted his life, the book is beautifully printed, and the illustrations, which are exquisitely drawn, have an appeal entirely in their own right.

The book begins with six chapters on arithmetic in which the reader will find something on the classical *arithmetica*, as well as a commentary on present-day commercial arithmetic, with some appraisal of the English system of units, e.g. the furrow might have been 'the distance oxen could pull a plough before having to pause for breath'. There is a nice treatment of the calendar with some mention of the Jewish and Moslem years. Then follow four chapters with algebra as the central theme, though the range is wide and we are soon considering the length of piano strings, the whirls on a nautilus and the arrangement of florets in the head of *Compositae*.

The two chapters on geometry and trigonometry have something to say about topology and such intriguing exercises as the four-colour problem, and there is a very worth-while discussion of the Fibonacci sequence and Euclid's golden section. The last chapter on statistics is, as one would expect, a careful discussion of normal distribution, scatter diagrams and correlation, but it is likely to prove too ambitious in scope for readers who have no previous acquaintance with this branch of mathematics.

There are a few blemishes; most of them are misprints but it is suggested that (p. 118) 2 is not multiplied by itself *five* times to make 32; the drawings (p. 156) should be altered either to perspective or isometric; it is a pity (p. 171) to say that the three angles of a triangle 'add up to a straight line'; 105·65 (p. 237) is not 105·6 (to one place of decimals); the formula for standard deviation should be quoted before it is used (p. 237).

These, though important, are of minor significance in comparison with the general excellence of the whole work. It deserves to be found in every school and training college library, for only by imparting to the younger generation the *thrill* of 'number' and of 'shape' can we hope to raise the standard of achievement in mathematics in the population as a whole; on this depends almost all our future development in science and technology.

W. J. L.

Other Books Received

Radio Astronomy. By F. Graham Smith. (Penguin Books Ltd.) 7*s*. 6*d*.

Isotopes. By J. L. Putman. (Penguin Books Ltd.) 8*s*. 6*d*.

Health and Hormones. (Penguin Books Ltd.) 4*s*.

Automatic Language Translation. By A. G. Oettinger. (Oxford University Press.) 80*s*.

Vibrations from Blasting Rock. By L. Don Leet. (Oxford University Press.) 27*s*. 6*d*.

Rival Theories of Cosmology. By H. Bondi, W. B. Bonner, R. A. Lyttleton, G. J. Whitrow. (Oxford University Press.) 9*s*. 6*d*.

The Secondary Technical School. By Reese Edwards. (University of London Press Ltd.) 15*s*.

Intelligence and Attianment Tests. By Philip E. Vernon (University of London Press Ltd.) 18*s*.

Russia's Rockets and Missiles. By Albert Parry. (Macmillan & Co. Ltd.) 25*s*.

Concise Physics. By T. M. Yarwood. (Macmillan & Co. Ltd.) 21*s*.

Atomic Physics. By J. M. Valentine. (English Universities Press Ltd.) 7*s*. 6*d*.

The Technique of Optical Instrument Design. By R. J. Bracey. (English Universities Press Ltd.) 35*s*.

Models and Analogues in Biology. Edited by J. W. L. Beament (Symposia of the Society for Experimental Biology). (Cambridge University Press.) 50*s*.

Materials for Nuclear Engineers. Edited by A. B. McIntosh and T. J. Heal. (Temple Press Books.) 75*s*.

Physical Chemistry for Students of Pharmacy and Biology. Second Edition. By S. C. Wallwork. (Longmans.) 18*s*.

The Moon: our nearest celestial neighbour. By Zdenek Kopal. (Chapman & Hall.) 25*s*.

Handbook of Abnormal Psychology. By H. J. Eysenck. (Pitman Medical Publishing Co. Ltd.) £6

Mathematics and the Physical World. By Morris Kline. (John Murray Publishers Ltd.) 25*s*.

Principles of Human Genetics. Second Edition. By Curt Stern. (W. H. Freeman and Co.) 68*s*.

Science and the Forester. By Leslie Wolff. (G. Bell & Sons.) 15*s*.

Tools of Biological Research. Edited by Hedley J. B. Atkins. (Blackwell Scientific Publications Oxford.) 37*s*. 6*d*.

A short history of Technology. By T. K. Derry and Trevor I. Williams. (Oxford, at the Clarendon Press.) 38*s*.

Plant Marvels in Miniature. By C. Postma. (George G. Harrap & Co. Ltd.) 45*s*.

British Nuclear Power Stations. By Rolt Hammond. (Macdonald & Co. (Publishers) Ltd.) 25*s*.

Magnetic Materials in the Electrical Industry. By P. R. Bardell. (Macdonald & Co. (Publishers) Ltd.) 32*s*. 6*d*.

Science and the Farmer. By F. R. Elwell. (G. Bell & Sons.) 15*s*.

Semi-Micro Qualitative Analysis. By T. A. Muir. (Heinemann.) 3*s*.

Practical Heredity with Drosophila. By Gordon Haskell. (Oliver & Boyd.) 10*s*. 6*d*.

Section Cutting in Microscopy. By H. F. Steedman. (Blackwell Scientific Publications Ltd.) 20*s*.

The Meaning of Evolution. By George Gaylord Simpson. (Oxford University Press.) 11*s*. 6*d*.

Current Probelms in Animal Behaviour. By W. H. Thorpe and O. L. Zangwill. (Cambridge University Press.) 45*s*.

Mathematical Puzzles and Diversions from 'Scientific American'. By Martin Gardner. (G. Bell & Sons.) 17*s* 6*d*.

The Challenge of Fusion. By D. Curry and B. R. Newmann. (D. Van Nostrand Company Ltd.) 41*s*. 6*d*.

Carnegie Institution of Washington Year Book 59. (The Lord Baltimore Press Inc.)

Frontiers of Astronomy. By Fred Hoyle. Mercury Books. (Heinemann Group.) 12*s*. 6*d*.

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